Know When to Fold 'Em: An Empirical Description of Risk Management in Public Research Funding

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Accepted at *Research Policy* (October 2019)

Abstract

Public research funding programs typically make grants with minimal intervention by program staff, rather than using a hands-on approach to project management, which is more common in the private sector. In contrast, program staff at the US Department of Energy's Advanced Research Projects Agency – Energy (ARPA-E) are given a set of real options with which to manage funded projects: abandon, contract or expand project budgets or timelines. Using internal data from ARPA-E, we show that active project management enables risk mitigation across a portfolio of research projects. We find that program staff modify projects frequently, especially project timelines, and these changes are more sensitive to poor performance than to strong performance. We also find that projects with a shortened timeline or reduced budget are less likely to generate short-term research outputs, compared to those of ultimately similar size. This evidence suggests that the practice of active project management, when combined with high upfront risk tolerance, can be used to enhance the productivity of mission-oriented public research funding.

Keywords: R&D funding, project management, real options, managerial flexibility

1. Introduction

Uncertainty is a fundamental challenge of managing technological change, and it is especially salient in the earliest stages of innovation (Rosenberg 1996). The knowledge that will result from any given research project is unknown *ex ante*, by definition. For a research funder, this uncertainty is a source of risk. A research project is generally funded on the premise that it has potential to generate information of value to the funder, i.e. leading to improved products or services in the private sector, or any of a wide range of societal benefits in the public sector. As a result, projects are risky for funders to the extent that they are unlikely to generate enough valuable knowledge to justify the cost of the investment.

There is an abundance of literature exploring how firms manage this risk. Many authors have noted that the systemic underinvestment in research and development (R&D) from the private sector is driven in part by the high level of risk and uncertainty (Arrow 1962; Nelson 1959; Griliches 1998). Public research funding is therefore an important tool to fill this gap and support high-risk R&D. Balancing the potential impact with the risk of technical failure for technology R&D projects presents a major challenge for government agencies, even more so when combined with the uncertainty associated with the application of the research and the economic impact of the technology.

Given the importance of the public sector in funding high-risk research activities, it is unfortunate that empirical evidence of risk management strategies within government research programs is lacking. One reason for this gap is the difficulty of obtaining data on decision-making within these programs. This paper seeks to add to the literature with a detailed descriptive analysis of the project management practices at the Advanced Research Projects Agency - Energy (ARPA-E), a grant-making organization within the U.S. Department of Energy (DOE). Since its start in 2009, ARPA-E has pursued high-risk R&D for energy technology. ARPA-E was created to be an agile organization, outside the traditional structure and bureaucracy of DOE, and this flexibility allowed them to adopt active project management, in the style of the Defense Advanced Research Projects Agency (DARPA) (National Research Council 2017).

There is an unresolved tension between, on one hand, the popular perception of DARPA as a model for breakthrough research (e.g. Belfiore 2010), and on the other hand, evidence from the literature that investigator freedom is a better strategy for motivating innovation (Azoulay et al.

2011, Manso 2011). And yet, despite extensive commentary and research on DARPA and its style of hands-on intervention (Bonvillian 2009; Fuchs 2010; Bonvillian 2019), to our knowledge, there has never been a quantitative study of how an actively managed public research funding program works in practice. Motivated by the need to maximize the impact of public R&D programs, particularly in the case of clean energy, we aim to fill this gap using a descriptive analysis of confidential program data from ARPA-E.

In this paper, we provide statistical analysis of ARPA-E program directors' (PDs) engagement with each project, including modifications to the terms of the project, and we show how this engagement relates to project outputs, such as publications and patent applications. We find that PDs have and frequently use the right to contract, expand and/or abandon research projects, especially in response to negative performance signals. We also find that contracted projects are less likely to produce research outputs, compared to projects of similar size, suggesting that active project management serves to maximize the short-term research productivity of ARPA-E projects. These findings contribute to the literature on research project management by showing, for the first time, how a public funding program can use managerial flexibility to mitigate exposure to technical risk.

The paper continues as follows: Section 2 provides background on risk and uncertainty in the context of research investments, as well as the context for ARPA-E and its approach to risk and project management. Section 3 describes the project-level data used in this analysis. Section 4 describes the econometric modeling results. Section 5 discusses interpretation of our findings and Section 6 offers some concluding statements.

2. Background

2.1. Project Modification to Manage Risk

In any portfolio of research projects, some projects will fail—they may fail to proceed through their planned research tasks due to unforeseen circumstances, or they may proceed as expected but fail to achieve their anticipated impact. Because the returns to innovation activities are notoriously skewed, research funders should expect a high rate of failure across their portfolio (Scherer and Harhoff 2000). A low rate of failure could indicate that the funder did not tolerate enough risk to achieve high returns overall. On the other hand, an excessively high rate of failure could threaten the funder's ability to demonstrate any positive outcomes in the short-term.

There is a tension in the literature around the degree to which research funders should be hands-on in actively managing the risk in their sponsored projects. At one extreme, some funders take a laissez-faire approach, allowing researchers to explore research directions based on their interests and intuition. This is the conventional approach to grant-making in the public sector. Many scholars have described the benefits of investigator freedom. Nelson (1962) recounts the invention of the transistor at Bell Labs as a success story for the practice of giving researchers flexibility to choose their research path. Azoulay et al. (2011) report the impressive outcomes of Howard Hughes Medical Institute (HHMI) awards, which give considerable freedom to the investigator, compared to NIH awards which adhere to pre-defined project objectives.

Programs that give flexibility and freedom to funded researchers are more likely to tolerate failure, which is thought to motivate innovative activity. A well-known model by Manso (2011) established that the threat of termination encourages researchers to exploit well-known actions, while continuation of research funding encourages exploration of unknown actions. HHMI investigators, for example, are funded for five years at a time and the majority of awards are renewed after the first five-year cycle (Azoulay et al. 2011). Tian and Wang (2014) found that tolerance for failure results in more innovation-related productivity within the venture capital industry.

At the other extreme, a funder may give authority to program managers and empower them to make decisions throughout the project, as is commonly done in the private sector. The value of flexibility in managing R&D investments has been studied previously through the lens of "real options," in an analogy to call and put options in finance. When there is uncertainty in some aspect of an investment, real options hold value beyond the expected value of the investments, because managers can adjust investments in response to new information (Trigeorgis 1996, Dixit and Pindyck 1994, Bowman and Hurry 1993, Bowman and Moskowitz 2001). Options for R&D projects include deferring, abandoning, contracting, or expanding them. Because of the high uncertainty of R&D projects, R&D investments may have greater value when real options are available.

Venture capital (VC) investors exercise real options through a stage-gate process that allows them to abandon a particular investment after a period of experimentation (Hurry et al 1992, Gompers 1995, Li and Chi 2013, Nanda and Rhodes-Kropf 2017). Firms also use real options in managing their internal R&D investments (Roberts and Weitzman 1981, Childs and Triantis 1999, Oriana and Sobrero 2008). The importance of flexibility for managing R&D has been highlighted by Huchzermeier and Loch (2001) and Santiago and Vakili (2005), whose models show that option value increases as certain types of uncertainty increase for a given R&D project.

A different stream of literature describes two strategies for active project management under uncertainty—learning and selectionism (Pich et al. 2002, Sommer and Loch 2004, Loch et al. 2006). Learning entails collecting information as a project proceeds and adjusting the plan accordingly, similar to the "improve" option introduced by Huchzermeier and Loch (2001). With a learning strategy, managers have the freedom to change project plans mid-course based on new information. Selectionism is a more extreme adaptation to uncertainty; rather than choosing one approach and refining it over time, a selectionist strategy entails pursuing many independent projects in parallel and then choosing the best one to proceed, i.e. choosing to abandon some projects and expand others. Results from Klingebiel and Rammer (2014) support this strategy; they showed that German companies who invested in a broad range of innovation projects had higher performance when they were able to selectively abandon projects at a later stage.

Given the evidence of effectiveness for both hands-off and hands-on R&D project management, it is unclear what outcome one would expect for an actively managed public research program. One impediment to resolving this tension is that the literature on managerial flexibility is focused on the private sector. We are not aware of any prior research that documents the actual practice of active project management for public sector R&D. Eckhause et al. (2009) create a model of public R&D acquisitions as a multi-stage competition between vendors and use it to construct an optimal portfolio. Lerner (1999) makes an analogy between venture capital and the US Small Business Innovation Research (SBIR) initiative, in that SBIR programs invest in small high-technology firms, but SBIR is implemented across many federal agencies which do not generally take an active management approach.

2.2. ARPA-E

ARPA-E was designed to fit the "ARPA model" for breakthrough research, pioneered by DARPA and characterized by organizational flexibility and empowered program staff (Azoulay, Fuchs, Goldstein and Kearney 2018). In its authorizing statute, ARPA-E was tasked with overcoming "the long term and high-risk technological barriers in the development of energy technologies" (110th Congress 2007, sec. 5012). An assessment by the National Academies found that ARPA-E had shown early signs of progress toward its goals (National Research Council 2017), and other work has shown that ARPA-E projects are highly productive at the interface of basic and applied research (Goldstein and Narayanamurti 2018), but there has been no research to-date on what role active project management may play in the agency's performance.

While still a much younger and smaller organization than DARPA, ARPA-E has carved out an identity as a funder of high technical risk projects—those that are judged to have relatively low probability of technical success—but high impact if the project succeeds.[1] Their first solicitation for proposals requested "high-risk concepts with potentially high-payoff" (ARPA-E 2009). It goes on to say, "The kinds of technologies most suited to an ARPA-E style development are those that still have significant technical risks to overcome, but promise to meet the future costs and scale of products that can deeply penetrate into consumer and industrial use." Goldstein and Kearney (2017) confirm that ARPA-E preferentially chooses to fund projects that are more controversial, i.e. with less consensus among external reviewers.

To balance their focus on high-risk research with the urgency of producing breakthroughs in energy-related science and technology, ARPA-E solicitations emphasize the importance of risk management for its projects. They judge applications on "the extent to which the Applicant manages risk, by identifying major technical R&D risks and clearly proposes feasible, effective mitigation strategies" (for an example, see ARPA-E 2015). They also explain, "ARPA-E will provide support at the highest funding level only for applications with significant technology risk, aggressive timetables, and careful management and mitigation of the associated risks" (ARPA-E 2015).

Part of ARPA-E's risk management strategy, and a fundamental feature of the ARPA model, is the hiring of top-tier PDs who are empowered with managerial flexibility (Bonvillian and van Atta 2011). As at DARPA, ARPA-E PDs have significant authority over the agency's research

[1] High risk here should be distinguished from scientifically unsound or unfeasible. ARPA-E FOAs state consistently that, "The proposed work may be high risk, but must be feasible."

investments. They select projects from among the submitted proposals, negotiate the terms of the project before it begins, and remain closely engaged with researchers over the course of the project, receiving quarterly progress updates and giving feedback on the same schedule. And most importantly for this work, PDs may choose to renegotiate the milestones, budget and timelines of research projects—in terms of real options, they may abandon, contract, or expand projects.

In the absence of any quantitative studies of how active project management functions at ARPA model agencies, it is not known how these PDs actually use their empowerment. Under the theory of real options, the flexibility given to ARPA-E PDs should enable the agency to mitigate risk by responding to project performance over time. By depriving failing projects of time, effort and capital, the program can bear lower risk than if all projects were maintained as originally negotiated. But without evidence of active management being implemented in a government agency setting, it is also plausible that ARPA-E PDs would rarely intervene in projects, perhaps due to familiarity with hands-off public grant-making. Or perhaps ARPA-E PDs would respond to struggling projects by extending their timeline or budget, because these are the projects that have the greatest need of support. This study documents how ARPA-E PDs used their managerial flexibility in practice.

3. Data

Over the course of two on-site visits to ARPA-E in 2016, we compiled datasets on the management of all projects in the history of the agency. We supplemented these datasets with additional data on publications, intellectual property, market engagement outcomes, and company founding year (collected by the authors from public information). All project data were anonymized on-site in order to protect the confidentiality of awardees. In this section, we offer a brief description of the project dataset, including the outputs associated with each project.

Table 1: Descriptive statistics for dataset of ARPA-E projects

Variable	Mean	S.D.	Min.	Max.
Duration				
Initial project length (years)	2.14	0.78	0.42	4.00
Final project length (years)	2.61	1.03	0.38	5.20
Net project extended	0.68	0.47	0	1
Net project shortened	0.12	0.33	0	1
Percent project length change	29%	49%	-87%	264%
Budget				
Initial award amount (million USD)	2.31	1.71	0.20	9.14
Final award amount (million USD)	2.51	1.83	0.20	9.14
Net budget increased	0.29	0.45	0	1
Net budget decreased	0.07	0.25	0	1
Percent budget change	15%	55%	-78%	607%
Status				
Fraction quarters green	0.47	0.31	0	1
Fraction quarters red	0.13	0.23	0	1
“Terminated”	0.10	0.30	0	1
External outputs				
At least 1 publication	0.43	0.50	0	1
At least 1 patent application	0.44	0.50	0	1
Market engagement	0.33	0.47	0	1
Any external outputs (>0 of 3)	0.74	0.44	0	1
All external outputs (3 of 3)	0.09	0.29	0	1

Note: Sample is the set of ARPA-E projects completed 2009-2015 (N = 233) for which quarterly status data were available. Project outputs are measured through Dec. 31, 2015.

Many ARPA-E projects are executed as partnerships between multiple organizations; for simplicity, we categorize projects by the organization type of the lead recipient. We separate private company awardees into two categories: startups (founded no more than 5 years prior to the project start date) and established firms. We limit our dataset to the 233 projects that ended on or before Dec. 31, 2015 and had quarterly status ratings recorded. Our status data cover quarters starting July 1, 2010 through July 1, 2015. When status data are missing, we carry the ratings forward from previous quarters.

Before a project begins, applicants negotiate with ARPA-E on the terms of the project, including duration, budget, and technical milestones. As the project proceeds, awardees submit quarterly reports addressing the progress made on each of the project's negotiated milestones. Following each quarterly report from the awardee, the PD rates the project's performance in terms of stoplight colors (red, yellow, or green). We construct a panel dataset of project-quarters, where status is quantified as a continuous variable where red = 1, yellow = 2, and green = 3.

According to our discussions with ARPA-E staff, the definitions of these colors are as follows: *green* for projects that are on track and meeting milestones; *yellow* for a project that has missed milestones but can recover; *red* for a project that has missed significant ("go/no-go") milestones and may not be able to recover. Ratings are given along several dimensions: cost, schedule, technical, and overall. From correlations among different status types across project-quarters, we see that the "overall" status primarily reflects the project's technical status and its schedule status (Table 2).

Table 2: Correlation coefficients for quarterly status types

	Overall Status	Technical Status	Schedule Status
Technical Status	0.8641		
Schedule Status	0.7147	0.6687	
Cost Status	0.3431	0.2749	0.327

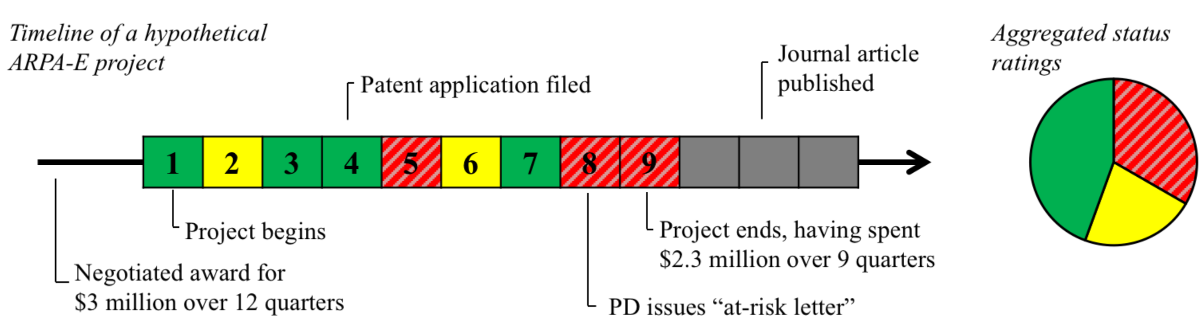
Only a small portion of project-quarters (7%) are overall red; 38% are yellow and 55% are green. Most projects (61%) never receive a red overall status rating. Status ratings are relatively persistent; 78% of project quarters are the same overall status as the previous quarter. For our cross-sectional project data, we focus on two continuous metrics for the aggregated internal status of a project: the percent of quarters in which it received a green overall status rating, and the percent of quarters with a red status rating.

Technical milestones may be re-negotiated and revised throughout a project. These milestone changes are a key component of managerial flexibility, and they occur regularly as well; 45% of projects experienced addition of new milestones or deletion of existing milestones. Projects also regularly change hands between PDs; 71% of projects experience at least one change in PD. Because PDs are hired on short-term contracts (three years with the possibility of renewal), projects that they initiate are often ongoing when they depart the agency. These projects continue under management by a new PD, so the recorded status ratings may not be from the same PD that originally recommended the project for selection.

Budgets and timelines are also frequently modified mid-project. Our analysis focuses on four indicator variables for the four possible types of net modifications that can be made to a project: increased budget, decreased budget, extended duration, and shortened duration. Projects are marked as having a budget change if the net difference between initial and final budget is greater than $20,000; projects are marked as having a change in project length if the net difference between initial and final project duration is greater than 60 days.

Some projects in our dataset are marked as "terminated." PDs typically send an "at-risk" letter to awardees as a warning in advance of terminating the project. For projects that are ultimately terminated, the project ended on average 164 days (1-2 quarters) after the at-risk letter was sent. As an example, we depict a hypothetical terminated project in Figure 1.

Figure 1. Quarterly status ratings and external outputs for a hypothetical ARPA-E project. This project was terminated after 9 quarters, rather than completing the originally negotiated 12 quarter-long project. Prior to being terminated, it received a green status rating in four quarters, yellow in two quarters and red in three quarters.



In order to address the effectiveness of project management practices, we need quantitative indicators of research progress. For each project, we collect publication data from Web of Science for all publications that acknowledge the ARPA-E award number or work authorization through Dec. 31, 2015. We obtained data from the Department of Energy on invention disclosures, patent applications and patents for ARPA-E projects through Dec. 31, 2015. ARPA-E tracks a set of follow-on outcomes internally for its current and former awardees: (i) private financing, (ii) additional government funding, (iii) company formation,[2] (iv) initial public offering, (v) acquisition, and (vi) release of commercial products; we combine these six metrics into a single binary indicator of some form of "market engagement" through February 2016. Finally, we create two aggregated metrics: one to capture at least one of these three external signs of progress (attained by 74% of projects), and another to capture projects that have attained all of these outputs (relatively rare, attained only by 9% of projects).

4. Results

4.1. Active Project Management at ARPA-E

Active involvement of the PDs in the execution of projects is a unique feature of ARPA-E's operations among other public research funders. In this section, we describe quantitatively how PDs use their authority to modify the terms of projects, and by doing so, tune the level of investment in a particular research effort. We model the relationship between the internal status of a project and the modifications made by ARPA-E PDs, to learn how PDs make decisions in response to project performance.

The data show clearly that ARPA-E PDs use real options often in the course of managing a set of projects. A large majority of projects (85%) are modified in some way from their originally negotiated budget or duration; the relative frequency of these modifications is illustrated in the Venn diagrams in Figure 2.[3] Project extensions are very common (68% of projects), and budget increases are second most common (29% of projects). Far more projects

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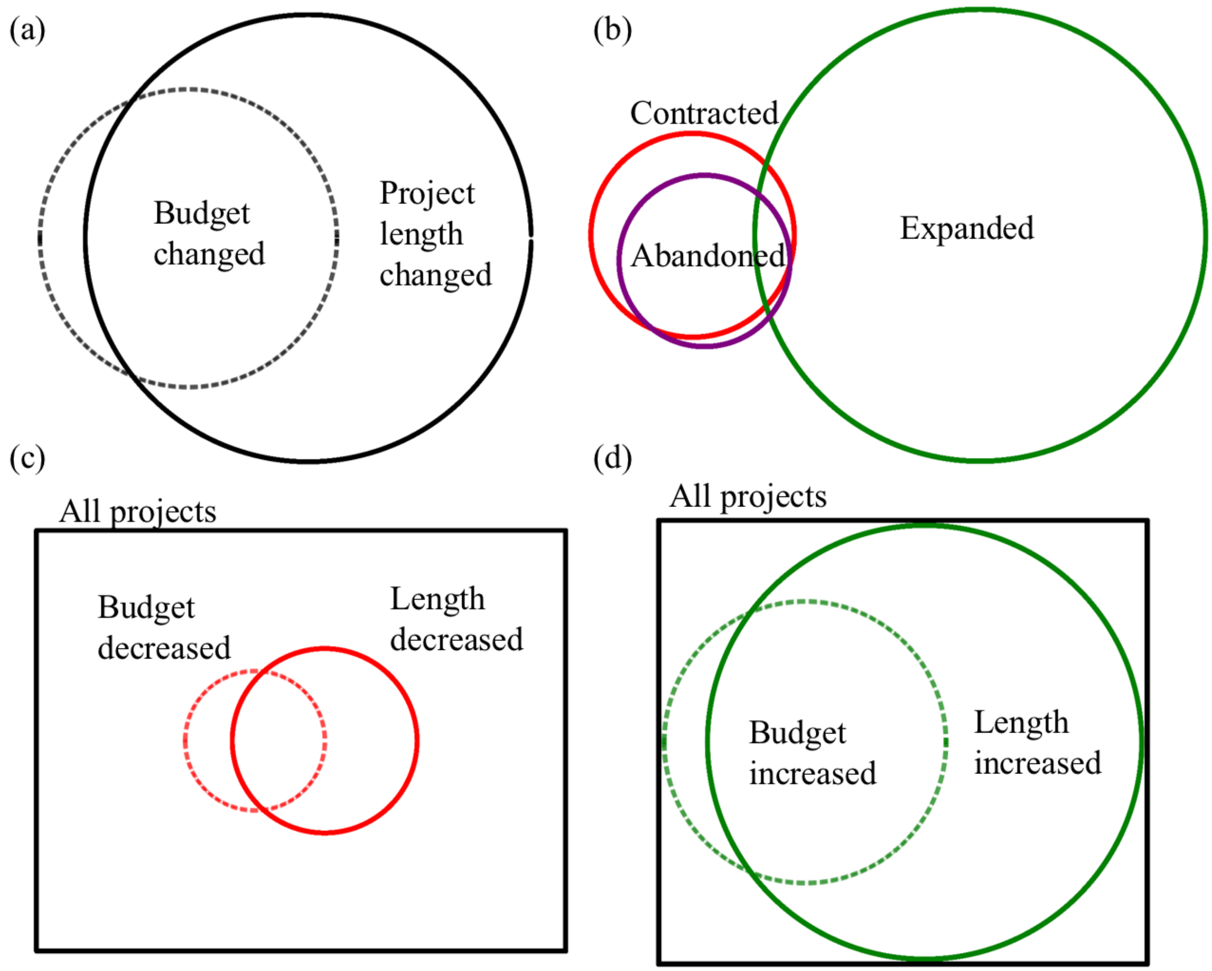
[2] Company formation includes academic awardees who would then go on to form a startup, as well as startup company awardees for which the ARPA-E award was their first funding.

[3] Projects may be modified multiple times throughout their lifetime; our analysis focuses on whether the net change was positive or negative.

are expanded in some way (increased budget or length) than are contracted (decreased budget or length) (Figure 2b).

The options to alter a project's budget and timeline can be combined; projects with modified budgets are largely a subset of projects that have their length modified (Figure 2a). An extreme version of contraction is an abandoned, or "terminated", project—these projects generally lose their entire remaining timeline and budget. On the opposite end of the spectrum, a project may be expanded both in terms of timeline and budget; of all extended projects, 37% of them also experience a budget increase, and the remaining 63% have no change in budget, i.e. "no-cost" extensions. It is rare for a project to be contracted in one dimension and expanded in the other; we observe this in only 4 projects (2% of the dataset).

Figure 2. Overlapping occurrence of various modifications to ARPA-E projects



Note: Venn diagrams were plotted using the Stata module *pvenn* by Gong and Ostermann (2011). Circles in each panel are proportional to the size of the designated group of projects. Circles in (c) and (d) are also proportional to the total number of projects, depicted by the rectangular outline.

Next, we compare these project modifications with our aggregated measures of project performance, e.g. fraction of quarters in which a project was rated green. By including both the proportion of green statuses and the proportion of red statuses, we can compare projects that are performing especially well (higher frequency of green), as opposed to simply avoiding failure (lower frequency of red); the omitted variable is "Fraction Quarters Yellow."

We perform ordinary least squares (OLS) regressions (Equation 1) to capture the linear probability of a particular project change (Y_i) as a function of the explanatory variables, e.g.

$X_{green,i}$ —the percent of quarters in which the project was rated green overall—while controlling for the technical program that funded the project (φ_i). In Table A1 in the Appendix, we show associations between additional control variables and one example project modification (a decreased budget), and we find a robust relationship with proportion of both green and red quarters.

$$(1) \qquad Y_i = \alpha_0 + \alpha_{\text{green}} X_{\text{green},i} + \alpha_{\text{red}} X_{\text{red},i} + \varphi_i + \varepsilon_i$$

We find several significant correlations between project performance and project modifications (Table 3).[4] In terms of budget changes, projects with relatively more green ratings are more likely to be rewarded with a larger budget (Model 1). Conversely, projects with more red ratings are more likely to be penalized with a decreased budget (Model 2). Project length changes, on the other hand, are not sensitive to the proportion of green ratings (Models 3 and 4). Projects with relatively more red ratings are less likely to be extended and more likely to be shortened or terminated; for a project that is 10 quarters long, being rated red during one additional quarter corresponds to an approximately 8% greater probability of being terminated.

Table 3: Association of internal status ratings with budget and project length changes

Dependent Variable:	(1) Budget Increased	(2) Budget Decreased	(3) Project Extended	(4) Project Shortened	(5) "Terminated"
Fraction Quarters	0.218**	-0.146**	0.063	-0.025	-0.066
Green	(0.093)	(0.065)	(0.086)	(0.056)	(0.064)
Fraction Quarters	-0.156*	0.282*	-0.612***	0.841***	0.752***
Red	(0.080)	(0.139)	(0.122)	(0.125)	(0.106)
Program F.E.	Y	Y	Y	Y	Y
Observations	233	233	233	233	233
R^2	0.237	0.224	0.224	0.430	0.377

Notes: Sample is all ARPA-E projects completed by Dec. 31, 2015. Standard errors in parentheses. All regressions are OLS with robust standard error. The models include a fixed effect for technical program. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

[4] One caveat to our analysis is that we use cross-sectional project data with aggregated status ratings over the course of a project. We assume that this measurement relates to the project's performance at the time when the PD decides to modify the terms, but this relationship only holds if the project ends shortly after the terms are modified, which is less accurate in the case of extended projects and increased budgets.

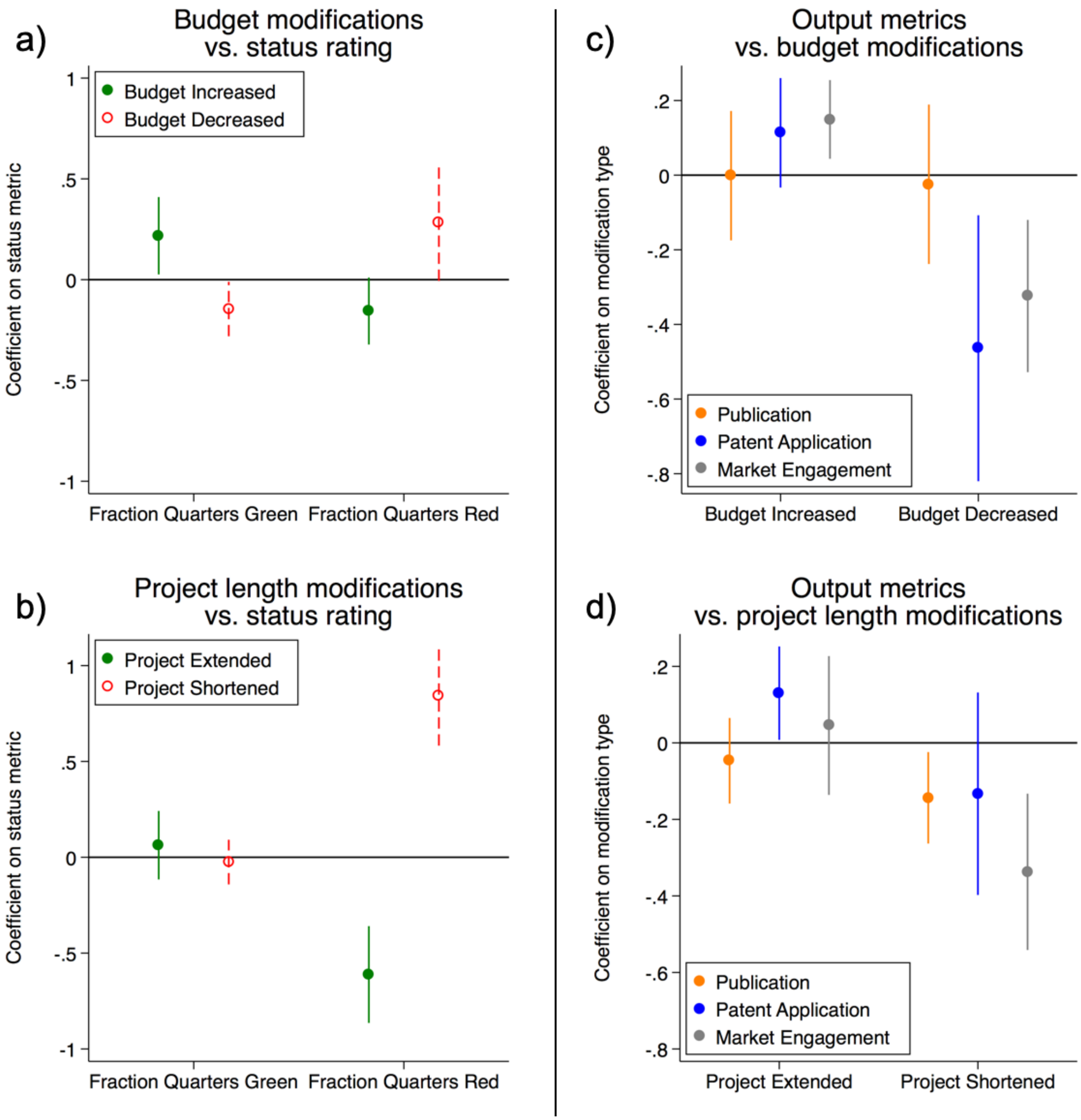


Figure 3: Plot of relationships between project modifications and (a, b) internal status ratings or (c, d) external research outputs. Coefficients are listed in Table 3, Table 4 and Table 5.

Several analyses in the Appendix add detail to these relationships between status ratings and project modifications. Table A2 shows the same regressions from Table 3 with a logit model. Again, we see that ARPA-E PDs modify project budgets in response to signals of both weak and strong performance, and they contract project length and terminate in response to weak performance. In Table A3, we predict the continuous amount of increase or decrease for a project's budget and length, in order to account for different degrees of change in project-level investments. Here, too, we find that project length changes show a strong response to red status; a project is only ever rated red can expect to be shortened by 5 quarters on average (Model 3), compared to one that is never rated red. And finally, we merge our observations of budget and timeline modifications into a set of combined metrics (Table A4), which mirror the results above for project length adjustments. For expanded projects (Models 1 and 2), we find a negative association with poor performance. And for contracted projects, we find the opposite—a positive association with poor performance (Models 3 and 4).

A panel dataset of project-quarters provides additional insights into the dynamics of active project management at ARPA-E. We observe the quarterly status of each project as well as whether its budget was modified in that quarter and by how much. Among projects that did have their budgets modified, most (78%) were only modified once. We also observe whether an "at-risk letter," which notifies awardees that their project is at risk of termination, was sent in a given quarter.

With the color rating encoded as a number (red = 1; yellow = 2; green = 3), we construct a variable for the rolling average of all previous status ratings for that project and test its correlation with budget changes and termination warnings (Table A5 in the Appendix). We find no significant relationship between budget increases and quarterly status. Budget cuts and warnings of termination, on the other hand, show a positive correlation. The odds of a budget cut taking place in a given quarter that is one unit higher average status (e.g. yellow vs. red) is ~40%. At-risk letters are even more strongly linked to status; the odds of an at-risk letter being sent in a given quarter are only 4% the odds associated with a one unit lower status.

4.2. Short-Term Productivity of ARPA-E's Portfolio

In the previous section, we documented how ARPA-E PDs' decisions to modify the terms of a project relate to their subjective performance assessments. Next, we connect these decisions to external metrics of performance. We note that our observation period is only six years, and evidence of impact for a research program may require significantly more time to accrue. The output metrics available for projects in the early years of ARPA-E's operation provides early evidence of the agency's impact. By analyzing the project-level determinants of these metrics, we can begin to understand the relationship between ARPA-E's approach to project management and the performance of its portfolio.

We seek to understand whether the decisions that ARPA-E PDs make to modify a project correspond to any measurable difference in the productivity of these projects. To do so, we include several control variables to account for inherent features of a project that impact the rate of publishing, patenting and/or market activity. In addition to the technical program, we account for organization type (University, Startup Company, Established Company, National Lab, and Non-Profit) and the amount of funding.

In order to account for the effect of investment size on productivity, we control for the actual funding amount, rather than the originally negotiated award amount. This allows us to compare projects that are retrospectively similar in execution, on the basis of ARPA-E's actual investment. For example, if a project is expected to receive $10 million but is terminated after $1 million is spent, then we cannot properly understand the performance of this project by comparing it to other $10 million projects. Instead, we compare the outputs of this project with those of other $1 million projects.

We test the relationships of project outputs with different measures of project modification: first in Table 4, whether a project's budget was increased or decreased (versus the omitted variable indicating "No Budget Change"), and in Table 5, whether a project was lengthened or shortened (versus the omitted variable indicating "No Project Length Change"). The OLS regressions (Equation 2) include fixed effects for technical program (φ_i) and organization type (γ_i). Table A6 in the Appendix shows the effect of including various control variables on the estimation of "market engagement"; relationships with budget changes are robust to these specifications.

(2) $$Y_i = \alpha_0 + \alpha_1 X_{1,i} + \ln(actual\ funding\ amount_i) + \gamma_i + \varphi_i + \varepsilon_i$$

Table 4: Association of project budget changes with external metrics

Dependent Variable:	(1) At Least 1 Publication	(2) At Least 1 Patent Application	(3) Market Engagement	(4) Any External Output	(5) All External Outputs
Budget Increased	-0.001	0.113	0.149***	0.100*	0.040
	(0.084)	(0.071)	(0.051)	(0.052)	(0.040)
Budget Decreased	-0.024	-0.464**	-0.324***	-0.363**	-0.128**
	(0.103)	(0.172)	(0.098)	(0.161)	(0.047)
Program F.E.	Y	Y	Y	Y	Y
Org. Type F.E.	Y	Y	Y	Y	Y
Ln (Final Award Amount)	0.080**	0.034	0.101**	0.025	0.054***
	(0.029)	(0.036)	(0.036)	(0.032)	(0.017)
Observations	233	233	233	233	233
R^2	0.348	0.369	0.306	0.445	0.162

Notes: Sample is all ARPA-E projects completed by Dec. 31, 2015. Standard errors in parentheses. All regressions are OLS with robust standard error, clustered by technical program.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table 5: Association of project length changes with external metrics

Dependent Variable:	(1) At Least 1 Publication	(2) At Least 1 Patent Application	(3) Market Engagement	(4) Any External Output	(5) All External Outputs
Project Extended	-0.047	0.130**	0.045	0.024	0.022
	(0.054)	(0.059)	(0.087)	(0.048)	(0.048)
Project Shortened	-0.144**	-0.133	-0.337***	-0.345***	-0.122
	(0.058)	(0.128)	(0.098)	(0.120)	(0.073)
Program F.E.	Y	Y	Y	Y	Y
Org. Type F.E.	Y	Y	Y	Y	Y
Ln (Final Award Amount)	0.085**	0.057	0.134***	0.052**	0.063**
	(0.031)	(0.035)	(0.043)	(0.025)	(0.024)
Observations	233	233	233	233	233
R^2	0.353	0.336	0.317	0.457	0.168

Notes: Sample is all ARPA-E projects completed by Dec. 31, 2015. Standard errors in parentheses. All regressions are OLS with robust standard error, clustered by technical program.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

We find several significant relationships between externally measured outputs and project modifications. For example, a project with a budget increase is roughly 10-20% more likely to receive some signal of market engagement, compared to a similar project with the same final budget but no modifications. Generally, the contraction options deployed by the PD have a stronger relationship with external outputs than expansion options. Budget decreases are negatively correlated with whether we observe a patent application, market engagement, any one output, or all three external outputs (Table 4), and similarly, project length decreases have a significant negative association with observing a publication, market engagement, any one output, or all three external outputs (Table 5).

Several additional analyses in the Appendix support our finding that projects with fewer outputs are penalized by PDs and those with more outputs are rewarded. Using a logit model to compare external metrics and project modifications produces largely the same results (Table A7 and Table A8 in the Appendix). We also check whether the relationship between outputs and active management are differentiated between riskier and less risky projects. As a proxy for risk, we use an indicator for whether or not a project was selected for funding despite a low external peer review score, i.e. "promoted" (Goldstein and Kearney 2017). There are no significant interactions between the binary "promoted" variable and the coefficient on project length or budget changes (Table A9 and Table A10).

These results demonstrate how externally-measured project performance relates to ARPA-E PDs' decisions to modify projects—decisions which we have shown in Section 4.1 relate to the PD's subjective assessment of project performance. In our final analysis, we close this loop by measuring how closely PDs' status ratings relate to our external markers of impact. Table 6 shows that there is a reduced likelihood of market engagement for projects that have a higher proportion of red quarters. Those projects are significantly less likely to attain any external output. Additionally, projects that are rated favorably by the PD are more likely to produce at least one publication and more likely to achieve all three external outputs that we measure: a publication, patent application and some form of market engagement.

Table 6: Association of internal status ratings with external metrics

Dependent Variable:	(1) At Least 1 Publication	(2) At Least 1 Patent Application	(3) Market Engagement	(4) Any External Output	(5) All External Outputs
Fraction Quarters Green	0.211**	0.246	0.060	0.112	0.172*
	(0.096)	(0.144)	(0.140)	(0.096)	(0.085)
Fraction Quarters Red	-0.040	-0.165	-0.440***	-0.473***	0.012
	(0.120)	(0.178)	(0.123)	(0.141)	(0.064)
Program F.E.	Y	Y	Y	Y	Y
Org. Type F.E.	Y	Y	Y	Y	Y
Ln (Final Award Amount)	0.064*	0.049	0.129***	0.041	0.052**
	(0.034)	(0.043)	(0.041)	(0.030)	(0.021)
Observations	233	233	233	233	233
R^2	0.365	0.343	0.306	0.466	0.174

Notes: Sample is all ARPA-E projects completed by Dec. 31, 2015. Standard errors in parentheses. All regressions are OLS with robust standard error, clustered by technical program.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

5. Discussion

In summary, our analysis uncovers three key features of ARPA-E's project management practices:

1) PDs frequently use their real options by adjusting project budgets and/or timelines. It is especially common for PDs to expand research projects.
2) PDs use budget and timeline options differently in response to performance signals. Timeline modifications are highly sensitive to negative ratings, while budget changes are only mildly sensitive to ratings of any kind.
3) Projects that are contracted or rated with poor performance are less likely to produce research outputs, compared to projects of similar size.

The first finding establishes that ARPA-E has implemented active project management in a real sense, beyond simply stating a policy of empowering PDs to modify projects. PDs abandon, contract, and expand projects regularly. Different types of adjustments are made with different frequencies; PDs expand projects far more often than they contract them, and they change a project's length more readily than its budget. These modifications allow PDs to adjust the allocation of resources among their managed projects. Technical programs are funded with a fixed total dollar amount, so any funds cut from one project's budget are recovered by the agency and may be allotted instead to other ongoing projects in the same program. Similarly, cutting one project short frees up additional resources for other projects, to the extent that staff time is a significant expense for the agency; PDs are limited in the number of projects they can actively manage at a time.

Our second finding shows that ARPA-E PDs use their flexibility to react midcourse to project performance—especially to poor performance. Rather than giving poor performers a lifeline by extending their projects, PDs prefer to reduce relative investment in failing projects. We find that project timelines are adjusted without sensitivity to proportion of green ratings, meaning that on average, PDs tend to tolerate yellow ratings (i.e. some missed milestones) without penalty in terms of the project length. However, if the missed milestones are significant, leading to a red status rating, PDs are less likely to extend these struggling projects beyond their originally negotiated timeframe, and they are more likely to shorten or terminate the project. This practice limits ARPA-E's exposure to risk by cutting short a project that shows signs of failing, or by depriving it of extensions given to other similar projects.

It is worth noting that, although we discuss investment risk at the project-level, PDs manage a portfolio of projects simultaneously. As a result, decisions about project modifications may not be made independently. For example, a PD may be more likely to cut an under-performing project short if they perceive a high opportunity cost based on the high performance of other projects. This portfolio effect is beyond the scope of our descriptive analysis, but could potentially offer a more detailed explanation of the management choices made by PDs.

Although we do not directly observe a PD's motivation or justification for modifying projects, we interpret the correlations between these modifications and project status indicators as the extent to which projects are modified in response to their performance. Given what is known about ARPA-E's program management style, we speculate that the decision to reward successful projects and cut losses for failing projects may be driven by the PD's sense of ownership over their portion of ARPA-E's portfolio. PDs are responsible for selecting which projects to fund, many of which are funded "out of order" or against the recommendation of external reviewers (Goldstein and Kearney 2017). Furthermore, PDs themselves may be judged by their peers on the results of their selections (Bonvillian and van Atta 2011). As a result, the

PD is motivated to maximize the productivity of the funds they were responsible for investing during their short tenure at ARPA-E (typically 3 years).

Our third finding shows that, by using their real options, PDs are indeed able to increase research productivity by cutting short projects that perform poorly in terms of observable, short-term outputs. We learn that contracted projects (which are more likely to receive frequent red status ratings) are less likely to have yielded any measurable success, relative to those of the same ultimate length or budget. Although we cannot establish whether red status ratings are made directly in response to lack of progress toward outputs, or to some unobserved aspect of performance that is correlated with outputs, PDs' subjective assessments are aligned with our selected external metrics of project performance—specifically with respect to project failure. The relatively weak correlations between output metrics and project expansions may indicate that PDs perceive these outputs (papers, patents and engagement with market actors) as a minimum requirement, rather than a signal of success.

In general, ARPA-E PDs chose to reduce investment on the least productive projects, and these decisions enhanced the short-term productivity of the agency by freeing up resources to be redirected to more successful projects. These findings provide support for one side of the divide between two opposing strategies of project management for public research: freedom for researchers, *à la* HHMI, or real options for managers as at DARPA. Although we do not attempt to compare the effectiveness of passive and active management (all the projects in our study were actively managed by PDs), our results add to the knowledge base surrounding active R&D management by describing its implementation at a public research funding agency for the first time.

Our findings about ARPA-E should be interpreted in the context of its clean energy mission. Mission-oriented research programs face a risk that does not apply to a program that aims to advance an area of science and technology more generally: the risk of a research advance that does not contribute to their mission. Consider an investigator at HHMI, who receives funding and then chooses to drastically change their research plans according to their own interests and preferences. If the research is impactful, this funding may be considered a success by HHMI. In contrast, ARPA-E designs funding solicitations around specific technical needs (e.g. a production cost target for energy storage materials) that have been selected to further the broader goals of the agency (advancing energy technology). A project that does not address this need is not a success for ARPA-E, no matter how impactful it is in other areas.

By using real options, ARPA-E PDs are able to continually direct funds toward the specific goals of the agency, rather than toward the general pursuit of scientific or technological progress. In this way, an ARPA-E PD is more similar to a private sector research manager than they are to program staff at the National Science Foundation or other non-mission agencies. A research manager in industry is likely to have specific research goals informed by the needs of their firm's technology area, and they are also likely to actively manage projects in pursuit of those goals.

The use of real options by ARPA-E PDs is somewhat analogous to the approach of VC investors. Similar to a VC investor becoming highly involved in a company's activities, recruiting executives or taking board seats (Amornsiripanitch et al. 2019), a PD can also be highly involved in a team's research. They can guide the research direction by adjusting project milestones (i.e. a learning approach) or, as we show in this paper, they can take a selectionist approach by terminating projects, similar to stage-gating by VCs. ARPA-E accepts prospective technical uncertainty upfront, as described by Goldstein and Kearney (2017), and then contracts or abandons under-performing projects. In this way, it appears that ARPA-E has earned its reputation as the venture capitalists of DOE (Grunwald 2010, LeVine 2014).

However, our results reveal an important difference between the concept of selectionism and the implementation of active management at ARPA-E. We find that ARPA-E PDs are not aggressive in either abandoning or contracting their investments. Rather than cutting all but the best projects, they appear to prefer expanding all but the worst projects. This distinction may relate to another difference—the way ARPA-E PDs select projects to fund in the first place. Selectionism calls for managers to pursue multiple trials due to uncertainty around the optimal choice *ex ante*, but ARPA-E projects face more than just short-term uncertainty regarding project outputs; they also face long-term uncertainty regarding the evolution of markets for energy technology. PDs often fund multiple approaches to a problem, such as alternative materials for power electronics or alternative battery configurations, but the uncertainty around these approaches will not be resolved over the course of a three-year project. This may explain why so many projects are encouraged to continue, as long as they are not perceived as failing.

We have shown that ARPA-E enhances its productivity and mission focus with the use of real options, and yet these gains must be weighed against the cost of an actively managed research funding program. Because an ARPA-E PD must be up to speed on the progress of each project and provide feedback on a quarterly basis, they can each only manage a dozen or so projects at a time. Compare an ARPA-E PD to a program manager who primarily interacts with grant recipients through annual reports and can oversee 60 projects at once; if an ARPA-E PD manages only 12, and both are paid \$150,000 per year, then ARPA-E is paying a premium of \$10,000 per year per project to have empowered PDs.[5] This is roughly 1% of the average yearly award amount for each project (\$0.97 million).

ARPA-E pays a premium to create real options, but the cost to the agency does not vary significantly with the extent to which these options are exercised. The PDs and awardees engage in a quarterly feedback process as a matter of routine. The additional time required for a renegotiation of project terms is apparently negligible in the case of expansions and contractions. One exception is project termination, which interviews with PDs indicate is somewhat more time-intensive and may be costly for the PD in terms of managing their individual workload.

Finally, we note an important similarity between actively managed research funding programs and those with investigator freedom: in both cases, project management decisions should be made by a qualified individual with technical training and expertise. At ARPA-E, decisions regarding budget and timeline are made by PDs rather than the investigator, but PDs are themselves technical experts on short-term contracts with the agency (Azoulay, Fuchs, Goldstein and Kearney 2018). This model allows ARPA-E to advance mission-relevant projects, while ensuring that decision-making power is still held by someone who is both well-informed on the status of the project and well-versed in the technical field.

6. Conclusion

Our study of project management at ARPA-E sheds light on how program design can enhance publicly funded high-risk R&D. Unlike other grant-making organizations within the federal government, ARPA-E's program management strategy empowers its staff to accept

[5] \$150,000 in PD salary to oversee a portfolio of 60 projects for one year amounts to \$2,500 per project, compared to \$12,500 per project for a portfolio of 12 projects.

technical risk upfront, and then modify the terms of funded research projects as they progress. Our descriptive analysis paints a picture of a public research agency that modifies projects in response to performance, such that failing projects are cut short. This evidence suggests that active project management can reduce risk and improve productivity of mission-oriented research programs, i.e. funders with specific goals for technology improvement.

It may seem intuitive that research managers would expand stronger projects and contract weaker projects, but it was not a foregone conclusion for ARPA-E as a public research funder. Alternative scenarios illustrate the value of our three key findings. First, we could have found instead that PDs used their options sparingly, consistent with expectations for program managers in traditional funding programs. Second, we could have found that PDs chose to expand struggling projects, seeing them in greater need of support, while cutting short projects that show signs of success and therefore require less public support than anticipated. And third, we could have found that PDs modified projects ineffectually, without any discernable productivity gains. The knowledge that PD choices did in fact mitigate risk for ARPA-E adds to our limited understanding of active management in a public research setting.

This study has some limitations, which we hope will inspire other researchers to further explore the topic of real options in public R&D management. Our data access did not include the content of project milestones or when and how they were revised, but a detailed analysis of these milestones would provide important insights. We still do not know what role the learning approach might play in public research management, e.g. whether riskier targets or poor performance make projects more or less likely to be redirected. Furthermore, the lack of experimental design prevents us from conclusively determining a causal relationship between the implementation of active management and project performance. Comparing outcomes for a set of actively managed projects, in the style of ARPA-E, and projects that are similar *ex ante* but administered by a hands-off program would be a valuable effort.

Acknowledgements

Our analysis originated as a consulting engagement with the National Academies for a study on ARPA-E. A.P.G was supported by a fellowship from the Belfer Center for Science and International Affairs. We are grateful for feedback from anonymous reviewers and from participants in the NBER Productivity seminar. We thank Laura Diaz Anadon, Pierre Azoulay, Paul Beaton, Iain Cockburn, Gail Cohen, Jeff Furman, Gilbert Metcalf, Venky Narayanamurti and Scott Stern for helpful discussions. Many thanks also to ARPA-E staff, in particular Dave Dixon, Ron Faibish, Andy Kim and Ashley Leasure, for their assistance in data collection. All errors or omissions are our own.

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Appendix

Table A1: Control Variable Testing for Predicting a Net Budget Decrease

Dependent Variable:	(1) Budget Decreased	(2) Budget Decreased	(3) Budget Decreased	(4) Budget Decreased	(5) Budget Decreased
Fraction Quarters Green	-0.121**	-0.146**	-0.158**	-0.167**	-0.165**
	(0.054)	(0.065)	(0.071)	(0.071)	(0.072)
Fraction Quarters Red	0.298**	0.282*	0.271*	0.260*	0.256*
	(0.117)	(0.139)	(0.136)	(0.142)	(0.143)
Ln (Init. Award Amount)				0.028	0.019
				(0.033)	(0.033)
Init. Project Length					0.019
					(0.032)
Program Fixed Effect	N	Y	Y	Y	Y
Org. Type Fixed Effect	N	N	Y	Y	Y
Observations	233	233	233	233	233
R^2	0.139	0.224	0.239	0.243	0.244

Notes: Sample is all ARPA-E projects completed by Dec. 31, 2015. Standard errors in parentheses. All regressions are OLS with robust standard error, clustered by technical program. Model 2 is the preferred specification for the main results.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table A2: Logit Specification – Association of Internal Status Ratings with Project Modifications

Dependent Variable:	(1) Budget Increased	(2) Budget Decreased	(3) Project Extended	(4) Project Shortened	(5) "Terminated"
Fraction Quarters Green	3.433**	0.005**	1.488	0.273	0.053
	[2.276]	[-2.561]	[0.757]	[-0.835]	[-1.427]
Fraction Quarters Red	0.150**	6.139	0.045***	1702.649***	111.696***
	[-2.222)	[1.435]	[-3.757]	[4.356]	[3.262]
Program Fixed Effect	Y	Y	Y	Y	Y
Observations	209	121	213	173	165
Pseudo R^2	0.174	0.322	0.160	0.464	0.392

Notes: Sample is all ARPA-E projects completed by Dec. 31, 2015. Exponentiated coefficients. *t* statistics in brackets. All regressions are logit with robust standard error, clustered by technical program. Our logit regressions use fewer observations than OLS, because technical programs without variation in the quantity of interest (e.g. 0% or 100% decreased budgets) are dropped from the analysis.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table A3: Continuous Measures of Project Modifications

Dependent Variable:	(1) Net Budget Change (Million USD)	(2) Fraction Budget Change	(3) Net Project Length Change (Years)	(4) Fraction Project Length Change
Fraction Quarters Green	0.381**	0.217	0.169	0.153*
	(0.169)	(0.129)	(0.135)	(0.082)
Fraction Quarters Red	-0.275	-0.128	-1.290***	-0.579***
	(0.194)	(0.097)	(0.268)	(0.121)
Program F.E.	Y	Y	Y	Y
Observations	233	233	233	233
R^2	0.252	0.174	0.408	0.308

Notes: Sample is all ARPA-E projects completed by Dec. 31, 2015. Standard errors in parentheses. All regressions are OLS with robust standard error, clustered by technical program.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table A4: Combined Measures of Project Modifications

Dependent Variable:	(1) Both Expansions	(2) Any Expansion	(3) Both Contractions	(4) Any Contraction
Fraction Quarters Green	0.175	0.106	-0.078	-0.093
	(0.106)	(0.095)	(0.046)	(0.071)
Fraction Quarters Red	-0.189**	-0.578***	0.271*	0.852***
	(0.083)	(0.125)	(0.158)	(0.100)
Program F.E.	Y	Y	Y	Y
Observations	233	233	233	233
R^2	0.243	0.254	0.412	0.229

Notes: Sample is all ARPA-E projects completed by Dec. 31, 2015. Standard errors in parentheses. All regressions are OLS with robust standard error, clustered by technical program.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table A5: Association of Rolling Average Status Rating with PD Actions

Dependent Variable:	(1) Budget Increased	(2) Budget Decreased	(3) "At-risk letter" sent
Rolling Average Status	1.209	0.359**	0.039***
	[1.091]	[-1.978]	[-11.721]
Observations	4221	4221	4221
Pseudo R^2	0.001	0.019	0.260

Notes: Sample is ARPA-E project-quarters recorded for July 1, 2010 through July 1, 2015. Exponentiated coefficients. *t* statistics in brackets. All regressions are logit with robust standard error.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table A6: Control Variable Testing for Predicting Market Engagement

	(1)	(2)	(3)	(4)	(5)
Dependent Variable:	Market Engagement	Market Engagement	Market Engagement	Market Engagement	Market Engagement
Budget Increased	0.191***	0.216***	0.193***	0.149***	0.128**
	(0.058)	(0.052)	(0.054)	(0.051)	(0.059)
Budget Decreased	-0.162**	-0.247**	-0.337***	-0.324***	-0.309**
	(0.074)	(0.088)	(0.103)	(0.098)	(0.110)
Ln (Final Award Amount)				0.101**	0.081*
				(0.036)	(0.046)
Final Project Length					0.037
					(0.072)
Program Fixed Effect	N	N	Y	Y	Y
Org. Type Fixed Effect	N	Y	Y	Y	Y
Observations	233	233	233	233	233
R^2	0.047	0.156	0.290	0.306	0.308

Notes: Sample is all ARPA-E projects completed by Dec. 31, 2015. Standard errors in parentheses. All regressions are OLS with robust standard error, clustered by technical program. Model 4 is the preferred specification for the main results.

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table A7: Logit Regression of Project Budget Modifications with External Metrics

	(1)	(2)	(3)	(4)	(5)
Dependent Variable:	At Least 1 Publication	At Least 1 Patent Application	Market Engagement	Any External Output	All External Outputs
Budget Increased	0.869	1.994	2.444***	3.425**	1.778
	[-0.297]	[1.600]	[2.926]	[2.327]	[1.149]
Budget Decreased	0.959	0.027*	0.077***	0.082**	--
	[-0.082]	[-1.836]	[-2.897]	[-2.122]	
Program F.E.	Y	Y	Y	Y	Y
Org. Type F.E.	Y	Y	Y	Y	Y
Ln (Final Award Amount)	1.680**	1.105	1.833**	1.138	2.750***
	[2.573]	[0.503]	[2.335]	[0.378]	[3.438]
Observations	216	205	212	184	126
R^2	0.261	0.251	0.234	0.283	0.146

Notes: Sample is all ARPA-E projects completed by Dec. 31, 2015. *t* statistics in brackets. All regressions are logit with robust standard error, clustered by technical program. Coefficients are exponentiated (odds ratios). Our logit regressions use fewer observations than OLS, because technical programs without variation in the quantity of interest (e.g. 0% or 100% market engagement) are dropped from the analysis. The association between achieving all external outputs and having a reduced budget is not measured because there are no projects that satisfy both conditions.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table A8: Logit Regression of Project Length Modifications with External Metrics

	(1)	(2)	(3)	(4)	(5)
Dependent Variable:	At Least 1 Publication	At Least 1 Patent Application	Market Engagement	Any External Output	All External Outputs
Project Extended	0.776	2.102**	1.336	1.111	1.829
	[-0.774]	[2.193]	[0.563]	[0.222]	[0.785]
Project Shortened	0.455**	0.434	0.036**	0.110**	--
	[-2.193]	[-1.095]	[-2.315]	[-2.331]	
Program F.E.	Y	Y	Y	Y	Y
Org. Type F.E.	Y	Y	Y	Y	Y
Ln (Final Award Amount)	1.664**	1.339	2.239***	1.524	3.436***
	[2.398]	[1.525]	[2.773]	[1.363]	[3.407]
Observations	216	205	212	184	119
R^2	0.266	0.211	0.249	0.277	0.152

Notes: Sample is all ARPA-E projects completed by Dec. 31, 2015. *t* statistics in brackets. All regressions are logit with robust standard error, clustered by technical program. Coefficients are exponentiated (odds ratios). Our logit regressions use fewer observations than OLS, because technical programs without variation in the quantity of interest (e.g. 0% or 100% market engagement) are dropped from the analysis. The association between achieving all external outputs and having a shortened project is not measured because there are no projects that satisfy both conditions.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table A9: Association of Project Length Modification with External Metrics – Interaction with Risky Projects

Dependent Variable:	(1) At Least 1 Publication	(2) At Least 1 Patent Application	(3) Market Engagement	(4) Any External Output	(5) All External Outputs
Net Project Length Change (Years)	0.021	0.117	0.074	0.086**	0.062
	(0.058)	(0.075)	(0.094)	(0.035)	(0.044)
"Promoted" # Net Project Length Change	-0.015	0.014	0.073	0.029	-0.024
	(0.064)	(0.060)	(0.061)	(0.037)	(0.055)
Program F.E.	Y	Y	Y	Y	Y
Org. Type F.E.	Y	Y	Y	Y	Y
Ln (Final Award Amount)	0.081**	0.066*	0.138**	0.050	0.069**
	(0.034)	(0.034)	(0.050)	(0.030)	(0.028)
Observations	200	200	200	200	200
R^2	0.320	0.333	0.325	0.393	0.155

Notes: Sample is all ARPA-E projects completed by Dec. 31, 2015. Standard errors in parentheses. All regressions are OLS with robust standard error, clustered by technical program.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table A10: Association of Budget Modification with External Metrics – Interaction with Risky Projects

Dependent Variable:	(1) At Least 1 Publication	(2) At Least 1 Patent Application	(3) Market Engagement	(4) Any External Output	(5) All External Outputs
Net Budget Change (Million USD)	0.038	0.167***	-0.026	0.070	-0.013
	(0.104)	(0.049)	(0.095)	(0.043)	(0.015)
"Promoted" # Net Budget Change	-0.004	-0.011	0.148	0.037	0.068
	(0.109)	(0.060)	(0.099)	(0.068)	(0.053)
Program F.E.	Y	Y	Y	Y	Y
Org. Type F.E.	Y	Y	Y	Y	Y
Ln (Final Award Amount)	0.071*	0.046	0.156***	0.050	0.074**
	(0.040)	(0.039)	(0.045)	(0.031)	(0.027)
Observations	200	200	200	200	200
R^2	0.321	0.345	0.311	0.384	0.154

Notes: Sample is all ARPA-E projects completed by Dec. 31, 2015. Standard errors in parentheses. All regressions are OLS with robust standard error, clustered by technical program.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$