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Energy technology R&D portfolio management: Modeling uncertain returns and market diffusion

John E. Bistline

Electric Power Research Institute, 3420 Hillview Ave, Palo Alto, CA 94304, United States

HIGHLIGHTS

- Analyzes energy R&D decisions with uncertainty in research outcomes and markets.
- R&D is shown to be more valuable in second-best planning and policy environments.
- Deterministic R&D approaches likely undervalue the optionality of technologies.

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ABSTRACT

The allocation of research and development (R&D) funds across a portfolio of programs must simultaneously consider uncertainty from research outcomes and from market acceptance of the resulting technologies. We introduce a stochastic R&D portfolio management framework for addressing both sources of uncertainty and present numerical results for energy technology R&D strategy under uncertainties in climate policy and natural gas prices. Numerical experiments indicate that R&D may be more valuable in second-best planning environments where decision-makers use expected-value approaches, and recourse investments occur after R&D has reduced costs. We also find that deterministic R&D valuation approaches likely overestimate the expected value of R&D success but undervalue the optionality and hedging potential of technologies relative to sequential decision-making approaches under uncertainty. The results also highlight the role of R&D in second-best policy environments.

1. Introduction

Managing technological change is an important objective for industry, government, and society. The development of new technologies and improvement of existing ones can enhance policy responses to challenges like climate change. R&D strategy has been a central concern for energy technologies in particular owing to their anticipated role in shaping environmental and economic outcomes.

The topic of designing R&D investment portfolios across a range of energy technologies has received greater attention following the Paris Agreement in late 2015. In particular, the launch of Mission Innovation and the Breakthrough Energy Coalition represent substantial pledges by governments and private investors to scale up public R&D efforts for low-cost clean energy technologies in the coming years. This increase in anticipated R&D expenditures also increases the urgency of developing tools and frameworks to spend these funds wisely, especially with many other simultaneous national and international efforts to promote energy innovation. For instance, the U.S. Department of Energy recently created the Office of Technology Transitions to work with national laboratories and industry to enhance technology development, transfer, commercialization, and deployment, including considerations related to energy R&D portfolio management.

Although R&D investments and innovation are focal areas of climate and energy policy, there is comparably little work on strategies to allocate fixed funds across a portfolio of energy technology R&D projects or to determine optimal levels of spending. For large-scale energy-economic and integrated assessment models, most frameworks assume that technological cost and performance characteristics improve exogenously over time (and are not influenced by changes in the regulatory environment or relative prices) or that endogenous learning will lead to technological change with increasing deployment [1]. It is uncommon to link R&D decision models with energy-economic models, even though the future technological state is important in regulatory design and implementation [2].

E-mail address: jbistline@epri.com

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Moreover, there is a need for new tools to cope with uncertainty and to provide decision-making support for R&D investments [3,4]. Stochastic and dynamic elements are pervasive features of the R&D process, including uncertainty in market conditions, in the relationship between R&D investments and technological outcomes, and in the ability to adjust decisions based on new information. This uncertain nature means that R&D outcomes are best described by probability distributions [5–7] with skewed outcomes [8,9], which suggests that focusing on average values may bias estimates of R&D returns. In particular, the processes of characterizing and incorporating uncertainty about market risks have been underrepresented in the literature. Although the National Research Council [4] regards these risks as "essential features of prospective benefits evaluation," their explicit consideration in a stochastic modeling framework has been limited due to the curse of dimensionality in large-scale energy models with many technologies and large state spaces [10].

This paper describes a framework to inform energy technology R&D decisions by incorporating uncertainty both in program outcomes and in diffusion markets. Our work uses a stochastic programming capacity planning model to assess the prospective benefits of energy R&D expenditures using two distinct steps—namely, modeling the relationship between R&D portfolio investments and potential outcomes as well as valuing these outcomes. This research makes contributions in both areas and applies these tools in a unified framework to explore how energy technology R&D decisions are influenced by uncertainties in research outcomes and potential market adoption.

This work contributes to the emerging literature combining energy technology expert elicitations with energy-economic models to support energy and climate policy decisions in the face of market and technological uncertainties. The decision framework and numerical modeling illustrate how multi-stage decision-making under uncertainty (as opposed to simple sensitivity or uncertainty analysis) can be combined with expert elicitations and decision theory models of R&D portfolio management. As discussed in Appendix A, these features are required to provide optimal R&D portfolio guidance for investors, policy-makers, researchers, and other stakeholders. The explicit consideration of uncertainty coupled with realistic engineering and cost assumptions for different technologies are required to directly inform questions of near-term R&D investments and policies. The framework presented and applied in this paper formalizes the process of allocating funds across projects with the highest expected returns. Comparing the marginal value of expenditures across different R&D programs requires the synthesis of knowledge across many domains to evaluate and articulate possible tradeoffs and opportunity costs.

One contribution of this paper is to inform questions about how to value prospective technological advances. Unlike previous frameworks using deterministic models to value R&D outcomes and assume market uncertainties are resolved when R&D decisions are made [11,12,2], this research investigates R&D valuations in a sequential decision-making setting under many simultaneous market uncertainties, which influence the extent and timing of diffusion.[1] Using the stochastic programming model from Bistline [13], this approach provides a more accurate representation of how allocation decisions are made in an uncertain market environment, where prospective conditions for electric sector investments and operations are subject to contemporaneous sources of uncertainty (Section 2.2). Although theoretical results suggest the effect of decision-making approaches on R&D valuation is equivocal [14], our numerical experiments indicate that R&D may be more valuable in second-best planning environments where decision-makers use simpler approaches for coping with uncertainty. These results suggest that traditional, deterministic R&D valuation approaches likely overestimate the expected value of R&D success relative to approaches that explicitly account for uncertainty using sequential decision-making but undervalue the optionality and hedging potential of technologies.

A second contribution is to represent R&D program heterogeneity by incorporating a range of technologies in allocative portfolio decisions. The empirical literature on energy technology R&D suggests that differences across technologies are even more important than differences across quantiles for a given technology, which makes heterogeneous parameterization important [8]. However, representing uncertain returns associated with innovation and technology-by-technology variation has been sparse in the energy modeling community, even though it has had a long history of investigating induced technical change [15–18]. Many studies in the energy R&D modeling literature assume learning for a single technology [19–24], as discussed in the review by [25]. When multiple technologies are incorporated, studies often use the same parameter values to describe different technologies [26,11,27,16]. Building on the analytical framework of [11], our model accommodates a range of technologies and R&D programs and offers a computationally tractable formulation for making R&D portfolio decisions under many simultaneous market uncertainties. We demonstrate how the model can capture distributions of returns to R&D spending and may yield skewed outcomes, especially if a technology has a wider market diffusion potential.

A final contribution is to parameterize the model using empirical information from expert elicitations. With limited exceptions [28,29,8], the literature focuses on average R&D returns and does not consider how allocations may influence the level of uncertainty associated with outcomes, which may be due to a lack of empirical grounding for calibration. Innovation production functions in this paper are calibrated based on the emerging energy technology expert elicitation literature, which quantifies uncertainty about the relationship between R&D investments and outcomes [30,29,2]. A novel feature of this work is the probabilistic treatment of R&D success, which is conceptualized as adjusting distributions over cost and performance metrics for technologies (Section 2.1). Although this treatment is consistent with the uncertain outcomes generated by R&D effort, it requires a technologically detailed model that can explicitly represent decisions under uncertainty, which are only now being introduced in the literature [31,32]. Using elicited data, the results underscore how updated expert elicitations and technology-specific R&D heterogeneity may influence program valuation.

2. Uncertainty, R&D success, and market diffusion

2.1. Conceptualizing R&D success

There are many ways to conceptualize the success of an R&D program [33]. First, R&D success can be modeled as increasing the (binary) probability of success in achieving specific technical or cost metrics. For instance, Baker et al. [34] define R&D success for solar technologies as meeting fixed targets for efficiency, operating lifetime, and manufacturing cost. Second, success can reduce the number of years required to reach specified technical or cost targets, which formalizes the notion that R&D success does not provide benefits in perpetuity. Blanford [11] adopts this framework in characterizing one "optimistic" technological pathway (i.e., with successful R&D) and another "pessimistic" pathway (i.e., one that achieves the same targets with a delay). A final way to

[1] Appendix A discusses related literature and research contributions of this work in greater detail.