Editorial

Energy Policy Special Issue on Defining Robust Energy R&D Portfolios

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1. The need to improve energy R&D decision-making

Decision makers in the energy sector — ranging from those setting national- or state-level technology policy, to firms deciding which new technologies to invest in, to consumers deciding whether to adopt the new technologies — are all faced with very complex decisions under uncertainty, both in terms of future fossil fuel use and other technology costs and in terms of future climate change policy and climate change related damages. In order to develop and to evaluate strategies for sustainable energy futures society needs to understand both the potential for future technological change; as well as, how that technological change will influence the evolution of the energy system, the economy, and the environment. Over the past two decades, there have been many calls for increased support for energy Research Development and Demonstration (RD&D) from a diverse set of important stakeholders and academics (e.g., American Energy Innovation Council, 2010; PCAST, 1997; PCAST, 2010; NCEP, 2004; Nemet & Kammen, 2007; Schock et al., 1999). These calls highlight the importance of energy R&D in meeting energy challenges globally and nationally.

The need to consider uncertainty about future technology costs to support decisions about R&D investments and other energy policies has been voiced by various prominent panels over the past 10 years. For example, the 2010 InterAcademy Council review of the climate change assessment of the Intergovernmental Panel on Climate Change (IPCC) had only one substantive (rather than process-oriented) topic in its recommendations — the treatment of uncertainty:

"*To inform policy decisions properly, it is important for uncertainties to be characterized and communicated clearly and coherently. … Quantitative probabilities (subjective or objective) should be assigned only to well-defined outcomes and only when there is adequate evidence in the literature and when authors have sufficient confidence in the results. … Where practical, formal expert elicitation procedures should be used to obtain subjective probabilities for key results.*" (InterAcademy Council, 2010). Similarly, the National Research Council (NRC, 2007) recommended that the U.S. Department of Energy (DOE) use probabilistic assessment based on expert elicitations of R&D programs in making funding decisions. Consistent with these suggestions, the U.S. DOE is recognizing the need to better integrate portfolio analysis methods with a focus on uncertainty at the currently on-going second DOE Quadrennial Technology Review, as demonstrated by a panel on the topic in its Cornerstone workshop.

Another important aspect of energy technology R&D decision making that often gets overlooked is the interaction of technologies in the marketplace: some technologies, such as solar power and storage, may be complements, while others, such as nuclear power and carbon capture and storage may be substitutes.

Finally, it is crucial that there is transparency in the process and in the assumptions about technologies (Chan and Anadon, 2014). The credibility of the decision-making process would be increased if estimates that incorporate a wide range of views (both internal and external to government) are widely available for inspection to stakeholders in Congress and industry.

There are a number of policy questions that are related to these calls for more systematic processes considering uncertainty. How should government agencies allocate funds across a range of R&D projects? How much in total should be expended on R&D and how should this be split between research, development, demonstration and deployment? What near-term investments and actions maximize future societal benefits? What would happen in the absence of any governmental increase in R&D spending? What kind of information or data is of most value when making these decisions? What is the role of spillovers and private investment in R&D? This special issue provides methods and frameworks for starting to address these questions, although some, in particular the last one, is beyond the scope of the work included here.

2. The genesis and content of this Special Issue

This special issue was germinated in a workshop co-organized by Erin Baker and Leon Clarke. The workshop, entitled *R&D Portfolio Analysis Tools and Methodologies*, was held at the U.S. DOE in December 2010, and brought together policy makers and analysts from multiple DOE offices with researchers doing cutting edge work on energy technology R&D portfolios. These researchers included representatives from groups performing expert elicitations, institutions managing integrated assessment models, and individuals working on developing decision frameworks for improving R&D decision-making under uncertainty. Among others, research groups from University of Massachusetts Amherst, the Kennedy School at Harvard University, Fondazione Eni Enrico Mattei, the Joint Global Change Research Institute, the Massachusetts Institute of Technology, and the Brookhaven National Laboratory were represented at the meeting. The workshop was based on the premise that an approach to portfolio analysis that considers uncertainty, interactions in the marketplace, and increased transparency would consist of three important aspects of R&D analysis. The first is expert elicitation to develop probability distributions over the future prospects of technology under different public R&D investment scenarios. The second is economic analysis of the impacts of technology improvements using energy-economic models. The third is the use of decision frameworks for portfolio optimization. A key output of the workshop was a list of 5 key priorities (Clarke and Baker, 2011), including:

(1) establishing an institutional structure for coordinating and communicating research aimed at understanding the prospects for energy technologies;
(2) improving the science of expert elicitations;
(3) developing and using alternate metrics for the calculation of benefits, such as energy security;
(4) exploring decision frameworks and associated tools; and,
(5) establishing a regular forum for interactions among researchers and decision makers.

In response to the findings of this workshop, the Technology Elicitation and Modeling project, known as TEaM, was established with support from FEEM, EMF, and the STPP program at Harvard University's

Kennedy School. The purpose of the TEaM project was to develop methods and frameworks for a set of activities crucial to defining robust energy R&D portfolios. The first activity involves collecting and harmonizing existing data. There are a large number of expert elicitation studies on future energy technology costs and performance. The TEaM project is aimed at integrating these studies with each other and with other relevant data on technology supply. The second activity is communicating the integrated data in a way that is useful to IAM modelers and policy makers. The third activity uses the harmonized expert elicitation data to run ensembles of energy-economic models. The fourth activity is implementing the resulting data sets into decision frameworks. TEaM, consisting of a group of researchers with overlapping interests across the three key areas of expert elicitation, economic modeling, and decision frameworks, held three meetings, in Venice (at FEEM, September, 1-2, 2011), Boston (at the Harvard Kennedy School, April, 5-6, 2012), and Snowmass (at the EMF meeting, July 31 and August 1, 2012). This special issue is the first output of the TEaM project.

In the first article in this special issue, Baker, Bosetti, Anadon, and Reis (this issue, 2014) present a summary of expert elicitation results across five technologies and three elicitation teams. This paper presents an original protocol for comparing and evaluating probability distributions based on human judgment in order to better understand what can and cannot be learned about the likely impact of R&D investments on future technology costs. The paper harmonizes elicitation studies, aggregates them, and communicates them. Specifically, the paper presents results on three large expert elicitations performed by researchers at FEEM, Harvard, and UMass, and includes carbon capture and storage (CCS), electricity from biomass, liquid biofuels, nuclear, and solar PV. The paper highlights the benefits of looking at multiple studies in defining more robust estimates. Indeed, different collection methods and questions can result in differences of the same magnitude as the differences resulting within a single study from a diverse set of experts. This paper provides a unique source of data for both policy makers and modelers, informing them on the range of beliefs among top technology experts from academia, the public sector, and industry on (1) the future cost of key energy technologies; and (2) the impacts on these costs of public investment in R&D. This analysis provides transparency, wide coverage of experts and studies, and explicit consideration of uncertainty.

Verdolini, Anadon, Lu, and, Nemet (this issue, 2014) — go a step further, using econometric methods to draw insights from the results of five studies focused on the cost of solar photovoltaics in 2030. This paper collects possibly the broadest existing range of expert elicitations done on one single set of technologies (solar photovoltaics), thus allowing a thorough evaluation of how features in the selection of experts and elicitation design might influence collected estimates. Among other things, the paper concludes that in-person elicitations are associated with lower central estimates, and that European experts tend to be more optimistic than their US counterparts. The paper also hypothesizes and tests how availability heuristics may shape experts responses. The paper finds no significant difference between the estimates provided by experts from the private sector, academia, or the government. In combination with a previous article using econometric techniques on nuclear elicitations (Anadon et al. 2013), this article suggests that the impact of various expert selection variables on results may be technology-dependent. This paper contributes to the science of expert elicitations by systematically and quantitatively evaluating the impact of different study design and expert selection features that have been discussed in other work (Morgan & Henrion, 1990; O'Hagan et al., 2006; Morgan, 2014). Finally, it provides a valuable source of data for policy makers and modelers.

Bosetti, Marangoni, Borgonovo, Anadon, Barron, McJeon, Politis, and Friley (this issue, 2014) address the second key aspect of energy technology portfolio analysis — the macro economic analysis of the societal implications of energy technology improvements. This study uses the combined probability distributions over the five technologies developed in Baker, Bosetti, Anadon, and Reis (this issue, 2014) as an input for three integrated energy economy models. These three models (WITCH, CGAM, and Markal-US), which are characterized by varying levels of flexibility, geographical and technological detail, and different structural assumptions, are run over a wide combination of technology performance assumptions and three climate policy scenarios. The simulation exercise has produced over six thousand model runs that have been analyzed ex-post with sophisticated global sensitivity analysis techniques. By looking at the implications of different future technological costs on multiple indicators (ranging from total emissions to policy costs) it is possible to detect what technologies play a key role under different climate scenarios and across different models. The main findings of the paper depend on the climate constraint. When emissions are not constrained (i.e., business as usual), the distributions of future technology performance lead to a world where the cost of nuclear energy is the most important driver of future emissions. In the climate-constrained scenarios, biofuels and electricity from biomass become important, as the first represents the main source of decarbonization of the transportation sector, and the second can be coupled with carbon capture and storage (CCS) to produce negative emissions. In addition to the main results, the paper is also unique in being the first ensemble effort to look into uncertainty and global sensitivity analysis.

Barron and McJeon (this issue, 2014) dig deeper into the impact of energy technology improvements using the GCAM model, with a special focus on how the benefits of low carbon technologies are impacted by assumptions about climate and socioeconomic pathways, based on the "New Scenario Framework" outlined in [1]
, with a focus the Representative Concentration Pathways [2]
and the Shared Socioeconomic Pathways [3]
. Similar to the above paper, they find that nuclear plays a significant role, with low-cost nuclear power (if it becomes a reality) a key facilitator of low-cost carbon abatement; this is robust across climate and socioeconomic pathways. They find that the next most significant technologies are bio-electricity and CCS; in both of these cases, however, it appears that reducing capital costs is much more important than improving, or even maintaining, high efficiencies. These two technologies also play different roles in different socioeconomic pathways, with bio-electricity (and liquid biofuels) providing a hedge in low-income, high population futures; while CCS is less valuable in these scenarios.

Baker, Olaleye, and Reis (this issue, 2014), tie the earlier papers together, using both probability distributions and economic outputs to analyze the optimal energy technology R&D portfolio under different decision frameworks for a range of different expert judgment studies. This paper provides an overview of decision-support frameworks that integrate uncertainty, and applies a one-stage and a two-stage decision framework to the range of elicitation results, using the economic outputs from the GCAM model. They find that it is crucial to consider both the prospects for advancement in individual technologies, and the interaction of those technologies with each other and with the economy, in determining R&D portfolios. It is not enough to know that a technology has significant potential for improvement; nor is it enough to know that a technology is crucially important in the economy. They also show that an investment in energy technology R&D still has value for addressing climate change, even in the absence of a climate emissions policy. Finally, they illustrate the importance of considering sequential decision problems under uncertainty; different technologies have different effects on the future flexibility to act, thus imparting more value than might be clear from a simple one-stage model.

3. Conclusions

The energy system is increasingly global and inter-related with other issues: there are growing connections between power and transportation; and food, air quality, land use, and energy poverty. This makes it crucial that decisions around energy R&D take into account overall welfare implications as well as multiple sources of uncertainty. This special issue presents research that brings forward a blueprint for a new approach to public energy R&D decision making that addresses these needs. The decision-focused methodology presented in these papers accounts for a large set of uncertainties (quantified through expert elicitations), and for aggregate welfare considerations (quantified through the use of integrated assessment models). This blueprint can be applied and expanded to include a larger set of models, future elicitation efforts, and more articulated decision making frameworks.

Beyond a description of the methodology, these papers also provide a systematic and transparent overview of existing data on the future costs of a set of energy technologies, and their implications in a range of economic models and decision frameworks, while highlighting important areas for future work. The different levels of data and output produced by this project provide key support for future modelling efforts and policy decision making.

In December 2014, representatives from governments, academia, and civil society met in Lima, Peru as part of the COP-20 to discuss actions that countries can take to meet the challenge of climate change. Indeed, the momentum is increasing, and public support for clean energy R&D is a crucial component of the actions that will be taken, with governments throughout the world investing at least $27 billion PPP in 2008 (Kempener et al., 2010) —investments that have been increasing, particularly in emerging economies. We remain hopeful that a systematic approach (such as that supported by the papers presented in this issue) will serve to support more effective and perhaps greater R&D investments.

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