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Large scale scenario analysis of future low carbon energy options

Olaitan Olaleye *, Erin Baker

Department of Mechanical and Industrial Engineering, College of Engineering, University of Massachusetts, Amherst, MA 01003, United States

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ABSTRACT

In this study, we use a multi-model framework to examine a set of possible future energy scenarios resulting from R&D investments in Solar, Nuclear, Carbon Capture and Storage (CCS), Bio-fuels, Bio-electricity, and Batteries for Electric Transportation. Based on a global scenario analysis, we examine the impact on the economy of advancement in energy technologies, considering both individual technologies and the interactions between pairs of technologies, with a focus on the role of uncertainty. Nuclear and CCS have the most impact on abatement costs, with CCS mostly important at high levels of abatement. We show that CCS and Bio-electricity are complements, while most of the other energy technology pairs are substitutes. We also examine for stochastic dominance between R&D portfolios: given the uncertainty in R&D outcomes, we examine which portfolios would be preferred by all decision-makers, regardless of their attitude toward risk. We observe that portfolios with CCS tend to stochastically dominate those without CCS; and portfolios lacking CCS and Nuclear tend to be stochastically dominated by others. We find that the dominance of CCS becomes even stronger as uncertainty in climate damages increases. Finally, we show that there is significant value in carefully choosing a portfolio, as relatively small portfolios can dominate large portfolios.

1. Introduction

Scientists largely agree that man's actions – past and present – are causing the earth to warm up (Solomon et al., 2007). Uncertainty still exists, however, about the severity of the resulting climate damages; and on the future of technological change in energy technologies. Technology policy, therefore, should account for different future realizations of climate damages and technical change. It is in this light that we evaluate potential technological advancements in six major low-carbon energy technologies, including Solar Photovoltaic, Nuclear, Carbon Capture and Storage, Liquid Bio-fuels, Electricity from Biomass, and Batteries for Electric Transportation.

In contrast to a previous study that investigated the role of technical change on climate policy through large scale scenario analysis (McJeon et al., 2011), the crux of our research is to explore the role of climate damage uncertainty on the relative impacts of the different energy scenarios, where a scenario is one possible energy future, represented by a set of cost and performance parameters over the six technologies. Our approach, which uses multiple models of differing levels of complexity and builds on the results of expert elicitations, allows us to study previously unaddressed questions on the relationships between energy technologies, and to rank future energy scenarios in terms of social utility.

In order to evaluate the likelihood of different possible future energy scenarios, we turn to previously performed expert elicitations. These studies follow an explicit protocol in order to elicit subjective probabilities over energy futures from a wide range of scientists and engineers (for a summary see Baker et al. (2015)). Hence, the results from these studies are inherently subjective. However, as a number of panels and studies have pointed out, expert elicitations are often the best way to characterize future uncertainty over events such as future technological breakthroughs (e.g. Boring et al., 2005; Mastrandrea et al., 2010).

Combining expert judgments with multiple models allows us to evaluate the expected social welfare of different energy technology research and development (R&D) portfolios, where a portfolio is a set of particular funding levels for each technology, and is associated with a probability distribution over scenarios. By combining probability distributions derived from the expert elicitations with the economic outcomes of technological advancement derived from economic models, we are able to evaluate stochastic dominance relations between different energy portfolios.

The central theme of this paper is to conduct a scenario analysis of promising future energy technologies with a view to aiding near term energy policy decision making. To do this, we address the following specific study goals. One is to understand the relative importance of advancement in individual technologies in an economy facing uncertain climate damages. Another goal is to understand the interactions between pairs of advanced energy technologies in the economy, and how these interactions change with uncertainty in climate damages. A

* Corresponding author.
E-mail address: oolaleye@engin.umass.edu (O. Olaleye).

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third goal is to examine for stochastic dominance between R&D funding portfolios and to understand how uncertainty in climate damages affect these stochastic dominance relations.

1.1. Approach

To address the questions raised above, two integrated assessment models (IAM's) are used, the Global Change Assessment Model (GCAM) and a stochastic version of the Dynamic Integrated Model of Climate and the Economy (DICE). The GCAM model is technologically detailed, allowing us to model the different mixes of futuristic energy technologies. The stochastically reformulated DICE model is computationally inexpensive, enabling large scale scenario analysis, while incorporating the dynamic impacts on social utility and decision making under uncertainty about climate damages. This approach enables us to examine how dependencies between technologies affect the overall benefits of having such energy technologies in our R&D portfolio when climate damages are uncertain, and to determine dominance relationships between different energy portfolios.

Our specific approach is as follows. We generate a large set of energy technology scenarios, encompassing combinations of price and performance parameters for our six technologies. These scenarios are first run through the technologically-detailed GCAM model, under a series of different carbon taxes, in order to estimate the impact of technological change on the cost of reducing carbon emissions.[1] We then use these estimated MACs to implement technological change into the DICE model. Our stochastic version of the DICE model includes uncertainty and learning about climate damages, and can calculate an expected utility associated with each energy scenario. This approach is shown in Fig. 1.

To understand the interplay between the different energy technologies, we conduct a simple regression analysis over the set of technology scenario outputs from the DICE model. The independent variables represent the level of technological advancement. The effect of the technologies on the resulting dependent variable, the expected utility, is then evaluated through the regression.

Finally, drawing on the previously performed expert elicitations, we assign probability distributions over the set of technology scenarios, conditional on specific R&D portfolio to obtain dominance relations.

The remainder of this paper is organized as follows: Section 2 provides a review of the literature and the background research leading to this work. In Section 3, we present the problem formulation, the models used in the study, our calibration of these models, the regression technique, and the calculation of probabilities. In Section 4 we present the results while Section 5 concludes the paper and gives future research recommendations.

2. Literature review and background on technologies

2.1. Literature review

One approach to thinking about the impact of R&D on climate change is scenario analysis (Clarke et al., 2008; Edenhofer et al., 2010; Kobos et al., 2006; Luderer et al., 2012; McJeon et al., 2011; Pugh et al., 2011; Shell Group, 2005). Scenario analysis entails the characterization and evaluation of internally coherent future *energy* states of the world that result from certain underlying presumptions about the initial states (Huss, 1988; Kahn and Wiener, 1967; Kahneman and Tversky, 1982; Swarta et al., 2004).

With scenario analysis, one has the choice to selectively, based on the purpose of the study and feasibility (e.g. Nakicenovic et al., 2000; Yohe, 1991), or comprehensively (McJeon et al., 2011) assess the resulting possible states of the world. Morgan and Keith (2008) show that selective scenario analysis leads to 'systematic overconfidence' as this causes the decision analyst to focus only on the scenarios modeled, and ignore possible extreme events that are not represented. Additionally the fact that most previous energy forecasts have been inaccurate (e.g. Craig et al., 2002; DOE, 1979; Kirsch, 2005; Lovins, 1976; Smil, 2003) emphasizes the importance of considering all possible outcomes. We use comprehensive scenario analysis, conditioned on the data available from the expert elicitations.

When using scenario analysis for decision analysis, a second choice exists, on whether to analyze scenarios deterministically (e.g. McJeon et al., 2011; Nakicenovic et al., 2000) or probabilistically (e.g. O'Neill, 2004; Pugh et al., 2011). Probabilistic scenario analysis entails assigning a probability distribution over the scenarios. Probabilistic comprehensive scenario analysis therefore has the advantage that it allows the relative evaluation of the full space of the scenarios in finite cases and the determination of the distribution over these scenarios within a consistent framework (e.g. Groves and Lempert, 2007; Schneider, 2001). On the other hand, the use of probabilistic scenario analysis has been faulted as inherently subjective (Grübler and Nakicenovic, 2001; Schneider, 2001) through the assessment of the probability distributions and possibly overly cumbersome. In this paper we present both a global deterministic scenario analysis and a probabilistic portfolio analysis.

Other approaches to R&D decision analysis exist including sensitivity analysis (e.g. Dowlatabadi, 1998), optimal portfolio analysis (Baker and Solak, 2011; Baker and Solak, 2014; Blanford, 2009; Blanford and Weyant, 2005; Bosetti et al., 2009; Diaz et al., 2011) and extreme space estimation (Moss et al., 2010). Recent work on expert judgments by Anadon et al. (under review), in which diverse expert elicitations are being harmonized and aggregated, also complements the probabilistic scenario analysis, optimal portfolio analysis and the extreme space estimation approaches. The study (Anadon et al., under review) noted that pooling of diverse opinions is a useful tool for characterizing uncertainty. They also note that technology interactions with each other and the economy play a significant role in characterizing the impact of R&D.

Though a few studies (e.g. Chow et al., 2003; Edenhofer et al., 2010; McJeon et al., 2011) have noted the existence of dependencies between the gains or cost reductions from advancement in energy technologies, no paper that we know of has developed a framework to quantitatively assess the degree and nature of these relations within an IAM framework. This study falls in the category of comprehensive probabilistic scenario analysis, where the uncertainties are in climate damages and technological outcomes. We rely on previous expert elicitations by Baker et al. (Baker and Keisler, 2011; Baker et al., 2008a, 2008b; Baker et al., 2009a, 2009b; Baker et al., 2010) to serve as inputs to assess the likelihood of technological development given R&D investment in the different technologies.

As several previous studies have noted, research using IAMs has some inherent limitations: the input technology characteristics have to be estimated as they are usually not well known (e.g. Baker and Solak, 2014); there exist significant questions on the appropriate methodology and time frame, for resolution of climate damages and mitigation of uncertainty (e.g. Grübler and Messner, 1998; Weyant and Olavson, 1999; Webster, 2002; Golub et al., 2014) and model bias and knowledge incompleteness (e.g. Risbey et al., 1996). Nevertheless, IAMs have proven to be a useful tool for gaining insights and informing policy (Kunreuther et al., 2014).

Another issue that has been discussed in the literature is uncertainty resolution. Most studies have focused on a two stage model for uncertainty resolution as this eases computational complexity considerably (e.g. Yohe et al., 2004; Webster, 2008). A few studies have used multistage models, but have had to simplify the IAM due to the computational cost (e.g. Webster et al., 2012); Crost and Traeger, 2012; Kelly and Kolstad, 1999). Some results indicate, however, that many of the insights can be gained by using a 2-stage model with perfect learning

[1] The term "carbon emissions" here actually refers to the CO_2 — equivalent of the set of all other greenhouse gases, as given in Van Vuuren et al. (2008).