Technical Report on Climate Change Technology R&D Portfolio Decision Making Under Uncertainty
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1 Introduction

In this project we developed an approach for incorporating uncertainty in the outcomes of technical change into climate change policy analysis. We combine expert elicitations and economic modeling to analyze the potential for Research and Development (R&D) into a range of energy technologies to impact climate change. Specifically, we developed probability distributions over Marginal Abatement Cost curves, conditional on U.S. government technology funding trajectories. As part of this project we produced a literature review on how uncertainty in endogenous technical change has been implemented in climate policy models [7].

The project had three main parts. Figure 1 illustrates the structure of the project; the actions placed within the box are part of the project; the actions outside the box are future applications of the outputs of this project. The first step of the project was collecting probabilistic data on a range of energy technologies through expert elicitations. The products of the elicitations include explicit definitions of endpoints for each technology, and probabilities of achieving those endpoints for given funding trajectories. The next step was to determine how the technologies would impact the abatement cost curve, if they achieve the defined endpoints. For this step we use MiniCAM, a technologically detailed integrated assessment model (IAM), to determine the impact of each technology on the Marginal Abatement Cost Curve (MAC). We then parameterize each technology's impact on the MAC. Finally, we combine the probabilities with the impacts on the MAC to derive multiple representations of the probabilistic impacts of R&D. As shown in Figure 1, these can then be combined with probability distributions over climate damages in technology policy models.

We focused on a selection of technologies from the electricity and transportation sectors. Within the electricity sector we have analyzed solar photovoltaics, nuclear power, carbon capture and storage (CCS), electricity from bio-mass (bio-electricity), and wind and solar grid integration. In the transportation sector we have analyzed batteries for electric and hybrid electric vehicles and liquid bio-fuels.

The rest of the report is organized as follows. Section 2 describes our methods; Section 3 describes the main findings; Section 4 describes key lessons learned; and Section 5 briefly summarizes.

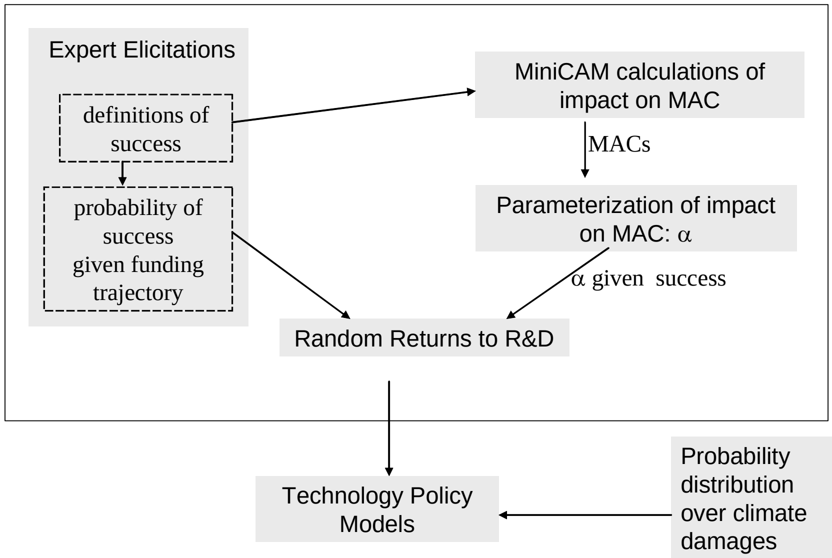

Figure 1: Framework of Project

2 Methods

2.1 Elicitations

We have completed the elicitation process for solar, nuclear, CCS, bio-electricity, and batteries. We are still in the process of collecting elicitations for liquid bio-fuels and wind and solar grid integration. For each technology, we worked with an initial set of 2-3 domain experts in order to prepare elicitation surveys. This consisted of three main steps:

1. Define a set of sub-technologies to asses. For example, for solar PV we assessed purely organic solar cells; CIGS; new inorganic solar cells; and 3rd generation concepts.

2. Establish a definition of success, or technological endpoint for each sub-technology. These definitions must be observable and unambiguous in order to allow for meaningful probability assignment.

3. Structure the elicitation. In this step we discussed with the experts all the potential hurdles that must be crossed in order to achieve the technological endpoints defined in step 2.

After preparing the surveys we circulated them to 3-6 further experts. We identified experts in academia, national labs, and the private sector. We purposely tried to find experts with a range of opinions. We emailed the surveys to the experts, and had a phone discussion about assigning probabilities, including some of the typical pitfalls. The experts then completed the surveys, including providing rationales for their answers, and returned them to us. At that point, we again contacted the experts to discuss their answers and ask further questions. The specific results have been presented in papers: solar [4] CCS [1] Nuclear [3] batteries [6].

Additionally, as part of this project we have been developing a theory for combining traditional Decision Analysis with economic modeling [13].

2.2 Impacts on the MAC

The expert elicitations provide us with definitions of success for improvements in the specific technologies. This section describes the applied analysis of the impacts that success, as defined in the elicitations, might have on the costs of CO_2 abatement. For each definition of success, we derive a Marginal Abatement Cost (MAC) curve.

2.2.1 The Marginal Abatement Cost Curve

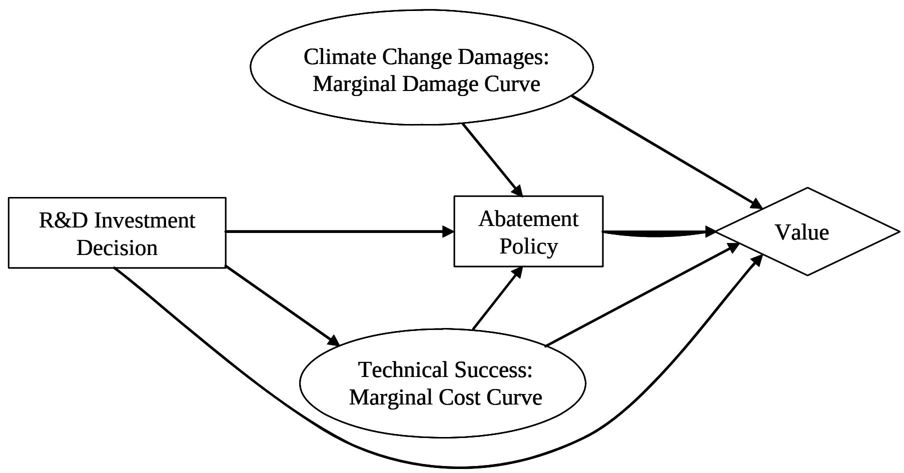

Figure 2: Influence diagram of the R&D investment decision

Many abstract, analytical models represent technical change in terms of its impact on the MAC. Understanding the impacts on the MAC is important because, when combined with a marginal damages curve, it determines the optimal amount of abatement, and implicitly, the optimal amounts of different technologies to be used in the economy. Figure 2 illustrates a high level influence diagram of the climate technology R&D investment decision. The R&D portfolio impacts the MAC, but in a probabilistic way. Abatement policy is chosen to minimize the combined cost of abatement and the damages from climate change, given current knowledge about climate change and given the current state of technology. Optimal abatement is found by equating marginal costs with marginal damages. The overall goal is to minimize the expected value of total costs, including R&D, abatement, and damages in this problem of sequential decision making under uncertainty.

Different technologies are likely to have a different effect on the cost curve. Figure 3 illustrates how the impact of technical change on optimal abatement varies by technology and by the severity of marginal damages. The solid upward sloping line represents the original MAC. The two dashed lines represent different types of technical change. The horizontal lines represent two levels of marginal damages. On the horizontal axis we show the optimal level of abatement in each case, where μ_{ij} represents optimal abatement given damages $i = H, L$ and MAC curve $j = 0, 1, 2$. Note that the technical change embodied by MAC_1 has no effect when marginal damages are low, but a significant effect when damages are high; the impacts of MAC_2 on optimal abatement are nearly the reverse. By paying attention to the impact of technology all along the curve (rather than just a point estimate), we gain information about how optimal behavior will change with changes in marginal damages. This project partially supported the development of a paper discussing these issues [5].

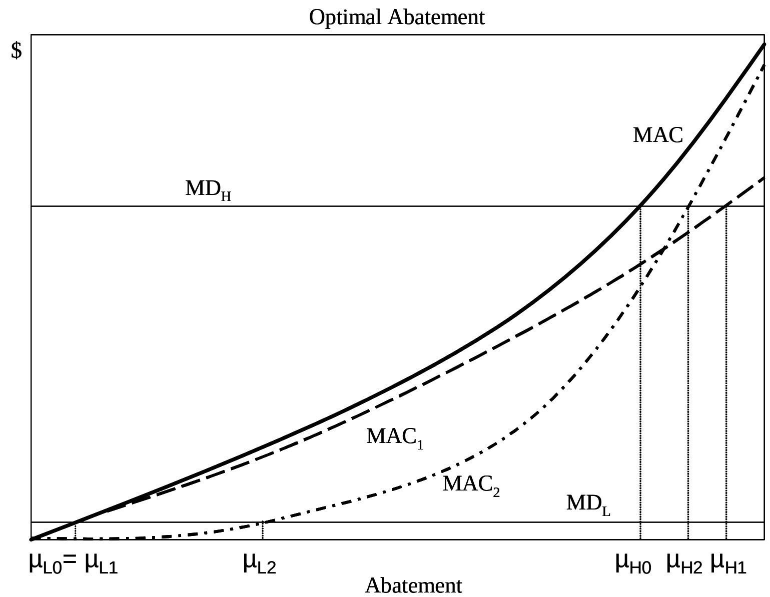

Figure 3: Stylized representations of technical change impact on the MAC; and resulting optimal abatement levels.

2.2.2 MiniCAM Implementation

For this project, we derive MACs for the year 2050 under different assumptions about technological pathways. The analysis was conducted using the MiniCAM integrated assessment model. MiniCAM is a global IAM that looks out to 2095 in 15-year timesteps. It is a partial-equilibrium model, with 14 world regions that includes detailed models of land-use and the energy sector. MiniCAM explicitly represents a range of electricity-generating technologies including various generations of nuclear power, multiple fossil generating technologies, solar and wind power, and electricity from biomass. Technology characteristics in MiniCAM are inputs to the model; the model does not include learning curves or other approaches to induced technical change.[1] We analyzed each technology separately. Assumptions for all technologies except the specific technology being analyzed are based on the version of MiniCAM used in the Climate Change Technology Program (CCTP) reference case [10].

The objective of the analysis was to develop marginal abatement cost curves under specific assumptions about the specific energy technologies at a particular time in the future, in this case 2050. These curves relate levels of emissions reduction to carbon prices, thus they approximate the marginal cost of emissions reductions. A range of carbon price paths were created leading up to 2050. In each path, the carbon price increases over time at the discount rate, modified by the average natural system uptake rate (i.e., consistent with a Hotelling [12] approach to resource

[1] See Brenkert et al. [8] and Edmonds et al. [11] for more discussion of the model.

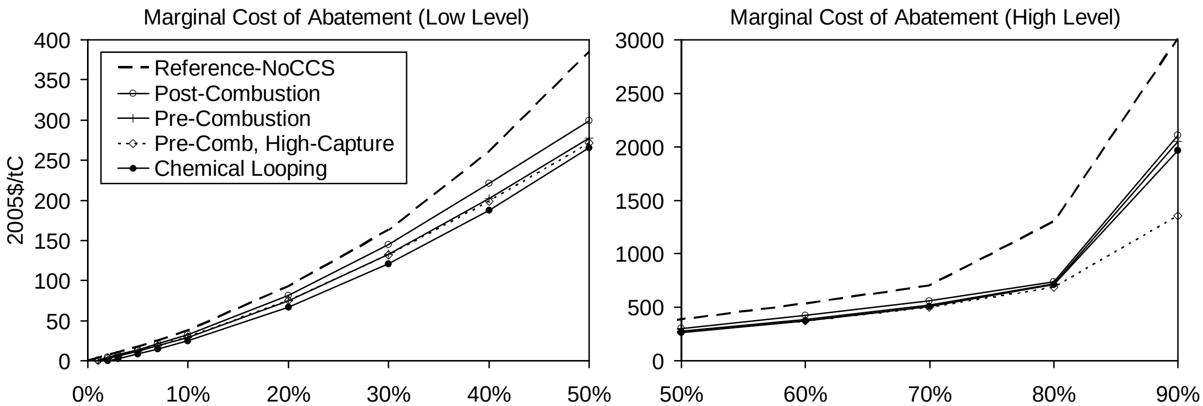

Figure 4: MAC curves under different assumptions for CCS. The left and right panels show the MAC for abatement between 0%–50% and 50%–90% for emphasis.

extraction modified by Peck and Wan [15]). In order to approximate MACs, we ran a range of price paths, and then plotted abatement in 2050 on the horizontal axis against the carbon price in 2050 on the vertical axis (See Figure 4 for an example of the impact of CCS). See [16] for another example of this kind of analysis. The relationship between abatement and the carbon price resulting from this analysis represents a marginal abatement cost function at a particular point in time. It should be noted that there is no single MAC in a future period, because the assumptions about capital deployment in previous time periods will influence the possibilities at any point in the future. An approach similar to this was used in the U.S. Climate Change Science Program (CCSP) scenarios to explain differences in the GDP impacts of CO_2 stabilization between different modeling groups [9].

2.2.3 Parameterization and Data Analysis

In order to facilitate analysis and computation, we parameterized the impact on the MAC for each technology. We found that CCS pivoted the MAC down, and thus can be represented through a single shift parameter. We found that nuclear and solar shifted the MAC to the right as well as pivoted it down somewhat. We used the data to perform initial analysis. We postulated likely funding orders for each technology category. For example, we calculated the expected impact on the MAC per R&D dollar; and considered a rule that would fund technologies in order of this metric.

3 Findings

This project is resulting in a database of information related to the technologies we have assessed. Along with the data and insights specific to each technology, we have garnered some general insights.

3.1 Elicitation Results

The elicitations lead to three general results. First, except for nuclear, the funding trajectories specified by the experts have been relatively low. Many funding trajectories have been on the order of about $10 million per year for 10 years. The reason the numbers have been fairly low, is that the experts are considering all the people that they are aware of who are working on these technologies, and have found that number to be fairly small. Thus, they felt that very large amounts of money would not buy a great deal of expertise, at least in the short run.

Second, we found a great deal of disagreement among the experts. One common theme is that some people are optimists, while others are pessimists. That is, some experts have low probabilities across the board, and others have high probabilities across the board. An important reason for disagreements among experts was that we were asking them to assess the probability of achieving certain cost targets. We needed to get this information in order to do follow-up economic analysis, but this is very hard for scientists and engineers to do. Thus, as part of this project, we developed a framework for combining the expert elicitations on scientific variables, with a bottom-up economic model of costs that takes into consideration returns to scale (see [14]). Finally, we purposely chose technologies that have a chance of a breakthrough. Almost by definition, these are very difficult technologies to assess, and are experiencing a great deal of change, almost daily. Thus, these results expose the fact that research into new energy technologies is a growing and exciting field. Hence, assessments vary a great deal from expert to expert. From this we conclude that the assessments may have most value in terms of sensitivity analysis and in calculating the value of better information.

Third, despite the disagreement among experts, we generally found that the assessments of the median expert were very close to the assessments of the average expert. Thus, if decisions must be made in the short run, we feel that the average over the experts can be reasonably used.

Finally, we found that for Biofuels technologies we had to develop a new model for structuring the elicitations. These technologies, more so than other technologies in other areas, are elements of a *system* of production. When the portfolio elements are components in a system, a hierarchical model describing system performance as a function of component performance allowed us to formulate practical assessment questions that would still support the necessary calculations.

3.2 Analysis results

We have completed the estimate of impacts on the MAC for solar [4] CCS [1], and Nuclear [3]. We found that (1) solar will only have a significant effect on the MAC if it can be successfully integrated onto the grid AND it can compete cost-wise with nuclear; (2) simply having CCS available and feasible had the largest impact on the MAC (as opposed to specific costs for the capture technologies); and (3) CCS has a large impact on the MAC at high levels of abatement, while nuclear has a large impact at lower levels of abatement. Thus, it appears that nuclear is a hedge against moderate climate damages, while CCS is a hedge against high climate damages.

Using data analysis we identified salient portfolios – places where the returns to R&D exhibit a sharp bend. Using average probabilities we found that the most salient portfolio for CCS involved a high investment in chemical looping and a low investment in post-combustion technologies. These results varied, however, when combining probabilities in different ways. See [1] for details. For solar the salient portfolio involved investments into both new inorganics and purely organic cells; for nuclear it was a high investment in improving Light Water Reactors.

4 Lessons Learned

Elicitations First, in order to do an elicitation with a high degree of confidence would require more resources. We recommend (1) having a domain expert (i.e. solar, CCS, etc.) present at each elicitation; (2) having some kind of remuneration for the experts in order to provide incentives to spend the time necessary; and (3) providing funding for extensive travel so that the elicitations can be face to face.

However, we believe that the high level of disagreement between experts can largely be explained by the highly dynamic nature of the fields at this point. For some of the technologies, understanding about their potentials were changing daily. Thus, taking the quick approach we took may be optimal, as long as the technology continues to evolve rapidly. That is, it may not make sense to spend considerable resources in analyzing a technology that may experience a breakthrough in the next year or two.

Second, as mentioned above, it was very difficult for the experts to provide probabilities over achieving particular costs. The ability to achieve a certain manufacturing cost depends on scientific breakthroughs, but also depends on a number of economic variables, such as demand and returns to scale. This is related to a third issue, which is whether or not the elicitation should be explicitly conditional on a carbon price. We purposely made our elicitations not conditioned on a carbon price, as our goal was to derive the impact on the MAC. However, the ultimate cost of manufacturing depends on scale, which depends on demand, which depends on a carbon price. Thus, in order to properly account for these dependencies we need to develop a process for combining elicitations on scientific variables (unconditional of a carbon tax) with economic models of demand (conditional on a carbon tax). See [14] for an approach to this problem.

Integrated Assessment Modeling Greater technological detail or accuracy in IAMs is important for facilitating these analyses. For example, the viability of solar power at high levels of deployment depends critically on the degree to which intermittent energy supplies can be integrated into the electric grid. In MiniCAM, this potential for this integration was dealt with in parameterized fashion. Either IAMs would need to obtain greater structural detail on the processes and issues in integration, or their parameterizations would need to be more effectively calibrated by domain-specific studies addressing specific technical questions such as these. An alternative would be to use more focused energy-only models to capture some of these dynamics. For example, for U.S.– only MACs, a detailed U.S.– only energy model such as NEMS might be used effectively.

There are many factors that influence technology deployment that cannot be captured structurally in economic models because they are non-economic and non-technical. For example, the deployment of nuclear power depends very much on public and political approaches to nuclear waste, nuclear proliferation, and nuclear safety. Similarly, large-scale deployment of CCS depends on regulatory approaches for permitting underground storage of CO2. These issues are not well-represented in energy-economic models. The recommendation here is not that these issues be incorporated into energy-economic models, but that they must be dealt with either as scenarios or as uncertainties in the analysis of technology impacts.

5 Summary

We have completed, or are in the process of, collecting and analyzing information on seven energy technologies, in regards to their potential impact on reducing greenhouse gas emissions. We have collected expert elicitations, relating U.S. government funding trajectories to probabilities of success. We then used an IAM to determine the impact on the MAC if the technologies were successful. Finally, we have performed initial analysis on portfolios of technologies. This project has partially supported the following papers: [1][2][3][4][5][6][7][13][14]. Using funding from NSF we intend to implement the data that we have collected into multiple climate policy models in order to derive insights into the science of energy R&D policy.

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