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Expert elicitations of energy penalties for carbon capture technologies

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ABSTRACT

This paper describes the results of expert assessments about the range of likely energy penalties (EP), the energy required to capture and compress CO_2, for coal power plants in 2025 for six capture technologies under three different policy scenarios. Expert opinions about the EP of each technology varied substantially. Measuring EP in terms of the fractional decrease in output per unit input, we found that a scenario of worldwide carbon pricing leads to a decrease in the mean energy penalty of 1–10% across the technologies, and a scenario of increased US government research and development (R&D) funding leads to a decrease in the mean energy penalty of 6–14%. EP for pre-combustion capture showed the smallest improvement from R&D and carbon pricing, while EP for post-combustion capture with membranes or "other" approaches showed the largest improvement. Although other factors will also affect costs, EP is a large component and these results suggest that capture costs are likely to fall both through investments in research and through the process of commercializing the technology in response to carbon prices. We summarize the challenges for each technology that were described by the experts, as well as the quantitative results.

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1. Introduction

Carbon capture and storage (CCS), combined with combustion of coal, gas, oil, or biomass to produce low carbon energy, is commonly seen as an important part of the mix of energy technologies under policies that limit carbon dioxide (CO_2) emissions (Bennaceur and Gielen, 2010; Clarke et al., 2007). A key question in climate change policy is what impact different policy and investment strategies will have on the technical viability and costs of energy technologies in the future (Finon, 2012; Popp, 2010). How much of a role carbon capture technologies will play depends in part on their technical feasibility and costs compared to other approaches (Watson, 2012). By understanding the effect of different policies on the evolution of CCS technologies, we aim to help governments and firms decide among different policies, as well as how to invest among capture technologies.

While carbon capture (CC) provides a potential way of reducing carbon emissions in response to climate change, many questions exist about future costs and technical feasibility of various methods proposed (Klara and Plunkett, 2010). Although historical data about how technology has advanced in the past provides some information (Rubin et al., 2007), each technology has its own idiosyncrasies and historical rates of change may not continue (Clarke et al., 2006). Knowledge is particularly poor in ex ante analysis of the results of R&D investments, which are inherently uncertain and lead to widely divergent outcomes (Scherer and Harhoff, 2000). For prospective studies of the future state of a technology, we rely on the judgments of those most knowledgeable about technological possibilities, which we obtain through direct discussion with the experts (National Research Council, 2005). Building on concepts in Rao et al. (2006), our study focuses on obtaining expert assessments of how key technical parameters affecting the costs of CC will evolve under different policy and funding scenarios.

We performed an expert elicitation, interviewing 15 experts and explicitly assessing their subjective probabilities over technological parameters for a set of six CC technologies, under multiple policy scenarios. We focused on energy penalty (EP), the energy required to capture and compress CO_2 from a power plant, as a metric of technological advances. Note that while energy penalty is a general concept, it can be measured in several ways. Our experts used 5 different metrics, which can be converted to each other. We define EP below in the terms used most frequently by the experts we interviewed: the fractional decrease in energy output per unit input. We also discussed qualitatively how the capital costs of these technologies might change through time.

A number of similar studies assessing the future of CC technologies have been done in recent years. Previous studies have ranged from very detailed technological assessments of one (Rao et al.,

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2006) or a few (Baker et al., 2009; Chung et al., 2011) specific technologies to high level assessments of CC technology in general, including studies focused on the cost of electricity (National Research Council, 2007) and others focused on individual technical and cost factors (Chan et al., 2010). Some of these studies were done via surveys and some with face to face interviews. Two main features distinguish our study. First, we consider a wide range of sub-technologies within CC, allowing us to get a picture of CC as a whole as well as how the different technologies compare with one another. Second, we focus on eliciting technological parameters rather than costs. Individuals who are experts on technology are not necessarily experts on finance, manufacturing, and commercialization, so we focused our elicitation on parameters clearly within their area of expertise. We separated technological improvements that might come from R&D investments from improvements that might come from economies of scale and learning-by-doing, for which historical data provide a basis for modeling separately (Nemet and Baker, 2009).

2. Methods

Expert elicitation (EE) is a formal process for obtaining experts' judgments about uncertain values, and quantifying those judgments in terms of probabilities that can be used in further analyses (Cooke, 1991; Meyer and Booker, 1991). The process is more intensive than surveys and more structured than simply collecting informed opinions. In a formal EE, a trained analyst familiar with probability encoding processes works together with an expert to develop probability distributions that accurately capture the expert's knowledge about the technical issues of interest. The process is both interactive and iterative, and includes discussions with the expert about the implications of his assessments and how the judgments will be used in subsequent analyses. A variety of approaches to EE are widely used and all include some combination of the following steps (Jenni and van Luik, 2010):

- Define study scope and objectives and verify the need for expert input
- Select experts who can provide the necessary judgments
- Structure the assessment
- "Train" the experts: familiarize them with the assessment task, how to quantify their judgments in terms of probability, and some of the common biases affect judgments under uncertainty
- Conduct the elicitation and provide feedback to the expert
- Aggregate the judgments
- Document the assessment and results.

2.1. Scope: policies and technologies

Our focus in this work was on exploring the potential effects of alternative policy scenarios on the future performance of several possible methods for capturing CO_2 from power plants. We grouped CC into eight areas of technology, which were sufficiently distinct to elicit clear responses and aggregated enough that multiple experts were available for each technology. For other taxonomies of CC see Figueroa et al. (2008) and IPCC (2005). Results for six of those technologies are reported here:

- Absorption: post-combustion using absorption via solvents, including MEA, ammonia, and novel solvents
- Adsorption: post-combustion using adsorption, including solid sorbents and metal organic frameworks
- Membranes: post-combustion using membranes, including ionic liquids
- Other PC: post-combustion using other approaches, including enzymes and cryogenics
- Pre-combustion capture, typically with integrated gasification combined cycle (IGCC)
- Oxyfuel: alternative combustion using pure oxygen rather than air

We also identified and explored two chemical looping technologies (Martinez et al., 2012; Marx et al., 2011), but did not compare them directly to the others because those two technologies are at especially early stages of development and their costs are more likely to be defined by factors other than energy penalty, e.g. reliability and capital cost.

We defined three policy scenarios involving public R&D funding and carbon pricing:

- *Scenario 1 (S1)*. No further US government funded research and development (R&D) in CCS (i.e. zero public investments in future years), current worldwide carbon policies are unchanged;
- *Scenario 2 (S2)*. No further US government funded R&D in CCS, worldwide carbon policy equivalent to \$100/t CO_2 price starting in 2015 and continuing indefinitely. This is about 20 times higher than the effective worldwide carbon price in 2010 of about \$5/t CO_2 (Nordhaus, 2010).
- *Scenario 3 (S3)*. "High" US government investment in R&D, defined as an annual investment level of about \$250 million per year from 2015 through 2025 for post-combustion capture, \$250 million per year for pre-combustion, and \$250 million per year for alternative combustion technologies. In this scenario current worldwide carbon policies are unchanged. These investment levels are slightly greater than 5 times the annual level of investment in carbon capture and sequestration R&D estimated between 2005 and 2012 (Gallagher and Anadon, 2012).

2.2. Structuring the assessment and selecting experts

To identify the most important technical factors for assessment, Rasmussen (2011) performed a sensitivity analysis of the effects of a range of parameters on the additional levelized cost of electricity due to CC. The challenge for this study was to select a set of technical parameters for each technology such that each parameter: (a) represents an important element in estimating the total cost of capture, (b) is an area where R&D funding could reasonably be expected to yield improvements, (c) is sufficiently detailed that researchers will be able to provide estimates of future values for the parameter under different R&D funding scenarios, and (d) is sufficiently aggregated that the effectiveness of R&D at improving each technical parameter can be considered independently. Finally, because experts would be asked to volunteer their time and a full elicitation of a single parameter requires multiple hours, we restricted the total number of parameters to be discussed to as few as possible.

In addition to the sensitivity analysis, we also received help from several advisors to identify appropriate parameters. The advisors were senior researchers in CCS technology with broad knowledge of multiple CC technologies. Most had participated in other EE studies and were familiar with the approach and the need to choose a small number of clearly defined parameters. Based on their input and Rasmussen's sensitivity studies (summarized briefly in the Supplementary Material (SM)), we determined that EP would be a useful representative summary metric on which to focus for the CC technologies considered here. The advisors also provided input into the definition of the policy scenarios.

We identified potential experts through a review of the literature and through discussions with the advisors. We sought representatives from industry, government, and academia, and prioritized recruitment on those who were expert on multiple CC

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