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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.

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 technologies. We focused mainly on US experts, since we were assessing US policies, but included two experts from the EU because of their breadth of expertise. The 15 participants are listed in the SM. Four of these experts work for one organization, and four work for a second organization. However, experts within each organization had different areas of expertise, and each provided input only on the technologies with which he was most familiar. As a result, only two technologies were evaluated by more than two people at a single organization. In all but two cases where a technology was evaluated by more than one person at a single organization, their median EP estimates were no closer to each other than each of them was to at least one other expert (that is, neither was the closest match to the other's assessment). Thus, we present the results of all experts individually. We note that this method of assuming independence of individual elicitations within organizations is also used in previous studies (Morgan and Keith, 1995).

Previous EE studies of CCS technology have asked experts to provide estimates of: (a) the probability of achieving technical threshold(s) (Chung et al., 2011), (b) the probability of achieving different levels of cost-of-electricity thresholds (Chan et al., 2010), and (c) the range of likely values for technical or cost parameters (Nemet and Baker, 2009). We used the latter approach here, and asked experts to provide their assessments of the EP in 2025 for each technology under each of the specified scenarios. They were asked to specify the 5th, 50th, and 95th percentile values describing their range of uncertainty about the future EP.

2.3. Conducting the assessment and providing feedback

We interviewed 13 of the experts in person, and two by phone. Interview duration ranged from 2 to 8 h and each expert evaluated from 1 to 7 CC technologies. Prior to the interview, each expert received a package of summary materials, including: (a) a project summary describing the goal and the focus of the elicitation, including a description of the various funding and policy scenarios, the CC technologies to be discussed, and the concept of the EP as a technical summary measure; (b) the sensitivity analyses that lead us to focus on the EP, which also provided information on the more detailed technical factors affecting the EP for each technology; and (c) a short description of the elicitation process itself and what the experts should expect during the interview. Each interview started with a brief review of the summary materials and a training presentation discussing the elicitation process and difficulties in expressing opinions in probabilistic terms, including illustrations of judgmental biases. Previous work has shown that increasing experts' awareness of potential biases, combined with an assessment approach that actively asks experts to consider surprises and their level of confidence in their estimates during the assessment process, can reduce their own biases during elicitation (Morgan and Henrion, 1990).

We used an informal protocol to guide the interviews, and the process was interactive, where we engaged in discussions with each expert as they worked through the development of their assessment of EP. Our goal was to obtain a robust picture of the potential energy penalties for carbon capture in the US, rather than an estimate of the energy penalty for a single technology on a tightly defined system. Accordingly, we had each expert start by describing the type and vintage of power plant for which they considered the technology most relevant. Generally, these were existing coal plants for post-combustion capture, new-build IGCC plants for pre-combustion capture, and new-build plants for oxy-fuel combustion. The experts also described a variety of base plants on which the technology could be deployed and included uncertainty about the base plant in their estimates of the range of EPs. For example, the most optimistic estimates (e.g. the 5th percentile estimates of the EP) may include the possibility of very high temperature super-critical plants with efficiencies of up to 46%. Most experts providing evaluations of post-combustion absorption and pre-combustion capture also began with a discussion of current estimates of the EP for those technologies, including a description of issues that gave them confidence in, or caused them to doubt, that those values will be seen in a full-scale implementation of the approach. After these grounding discussions, each expert identified challenges involved in each technology, areas where improvements would lead to reductions in the EP, and then worked through their assessment of how much of a reduction in EP would be possible or likely under each scenario to arrive at quantitative assessment of the distribution. We took notes and recorded their assessments, and for each technology we reviewed and compared the resulting assessments with the expert during the interview. We prepared a summary of each interview including both the qualitative discussion and quantitative assessment results and asked each expert to review it for accuracy. Although the experts were given the opportunity to revise their assessments after reviewing the summary, none did so.

2.4. Energy penalty metrics

One of the principles of good expert elicitation practice is to conduct the assessment in terms most relevant to each expert, rather than asking them to think in unfamiliar units. Because the term "energy penalty" can be quantified in several ways, we asked each expert how they define and quantify EP, and we carried out the assessment in those units. They used five different metrics for EP, three based on the estimated efficiencies of a power plant with (η_{withCC}) and without (η_{ref}) CC, and two based on more direct estimates of the amount of energy required to capture a specified amount of carbon. In this paper we present the EP results using the metric that was preferred by the majority of our participating experts: as the fractional decrease in net energy output per unit of energy input

$$\text{EP} = 1 - \left(\frac{\eta_{\text{withCC}}}{\eta_{\text{ref}}}\right). \tag{1}$$

Table 1 shows all five metrics used by the participating experts, and compares their values for three hypothetical plants. EPs of 0.2, 0.25, and 0.3 using metric 1 are shown, along with the equivalent EP using other metrics for the same hypothetical plant. See the SM for further discussion.

2.5. Fitting probability distributions to assessed points

Experts provided their 5th, 50th, and 95th percentile estimates of EP for each technology/scenario combination, which we used to define a probability distribution over EP. The probability distribution was defined by fitting various functional forms to the assessed points, after converting to the common metric above, using @Risk® software (Palisade, 2012). For almost all the assessments, there were multiple distributions that provided excellent fits, with only trivial differences in the fit statistics. When multiple well-fitting distributions were available, we attempted to select: (a) distributions that were bounded rather than unbounded, (b) distributions with lower bounds greater than zero, (c) distributions that imposed as little additional structure on the assessed points as possible (e.g. uniform distributions), and (d) the same distributional form to represent the assessment for each scenario for a given technology and a single expert. In almost all cases the chosen distribution had a root-mean-square error of less than 10^{-15}. For those few assessments with lower fits, the best fitting distribution was used, and in a very small number of cases a piecewise linear distribution was defined to represent the assessment.

Table 1
Comparison of alternative energy penalty metrics for example base plants.

	Plant 1 500 MW base plant with efficiency, $\eta_{ref}=0.40$			Plant 2 500 MW base plant $\eta_{ref}=0.36$			Plant 3 750 MW base plant, $\eta_{ref}=0.40$		
Metric 1: fractional reduction in output energy per unit of input energy, $1-(\eta_{withCC}/\eta_{ref})$	0.20	0.25	0.30	0.20	0.25	0.30	0.20	0.25	0.30
Metric 2: reduction in plant efficiency ($\eta_{ref}-\eta_{withCCS}$)	0.08	0.10	0.12	0.72	0.90	0.108	0.08	0.1	0.12
Metric 3: fractional increase in input energy per unit of energy output, $(\eta_{ref}/\eta_{withCC})-1$	0.25	0.33	0.43	0.25	0.33	0.43	0.25	0.33	0.43
Metric 4: decrease in energy output in MW for a base plant of a specified size	100	125	150	100	125	150	150	187.5	225
Metric 5: MJ energy required per kg CO_2 captured and compressed	2.5	3.1	3.8	2.5	3.1	3.8	2.5	3.1	3.8

Note. η_{ref}, the efficiency of the base plant without carbon capture; η_{withCC}, the efficiency of the same base plant with carbon capture.

For some technologies and scenarios, one or more experts judged that the technology would not be developed at all, or would not be developed to the point where it would be possible to estimate an EP. To clarify and emphasize the focus the technological feasibility and performance in this study we asked those experts to estimate the probability that the technology would be technically viable (i.e. sufficiently developed, tested, and implemented that an EP could be estimated), and then to provide their estimates of the EP conditional on the technology being technically viable. The resulting assessments were treated as a mixed distribution, with a discrete probability that the technology is not technically viable, and a continuous distribution fit to the conditional assessments.

2.6. Combining individual results

While individual assessments can be used, it is often of interest to combine or aggregate the assessments. A common approach to the mathematical aggregation of expert assessments is called a "linear opinion pool" (Clemen and Winkler, 2007). For this application, the aggregate distribution for EP can be written as:

$$f(\mathrm{EP})=\sum_{i=1}^{n} w_i f_i(\mathrm{EP}) \qquad (2)$$

Where $f(\mathrm{EP})$ is the aggregate probability density on EP, i's represent the individual experts, w_i is the weight assigned to expert i's assessment, and $f_i(\mathrm{EP})$ is expert i's probability distribution on EP. We use $f_i()$ to represent the distribution generally, whether it be a continuous distribution, a mixed discrete-continuous distribution, or a linear combination of distributions. For this study we weight each expert's input equally.

3. Results

3.1. Individual assessment results

Fig. 1 shows the expert assessments of the EP for each of the six technologies. Each expert was randomly assigned an identifier from E1 through E15 (as shown on the y-axis) to protect their anonymity. The figure shows the median estimate with a marker, and the range between the 5th percentile and the 95th percentile as error bars. Assessments for each of the three policy scenarios are shown as separate lines.

Most experts interviewed provided assessments of only a subset of the six technologies of interest, due either to time constraints or their own assessment of their knowledge of the technologies. When time constraints prevented assessment of all technologies, the expert was asked to evaluate the technologies with which he was most familiar. Absorption was evaluated by the largest number of experts (12) and "other post-combustion" was evaluated by the smallest number (4). In Fig. 1, the probability that the technology is technically viable is shown to the right of the conditional assessments, for S1, S2, and S3, in order. Where no values are shown, the experts did not state any uncertainty about technical viability but simply provided their EP estimates and the probability of viability is assumed to be 1.

As described above, for absorption and for pre-combustion capture, most experts began their assessments by discussing their estimate of the "current" EP, and how that might change between now and 2025 under each scenario. Although the current EP was not formally assessed in the same manner as the 2025 EP under the three scenarios was assessed, Fig. 1 also shows the value (or mid-point of the range) provided by each expert for the current EP for those two technologies for comparison.

3.1.1. Qualitative description of technology challenges

In the process of developing their assessments, the experts discussed their reasoning and highlighted distinct challenges for each technology, which are summarized below.

Absorption. At least 4 experts explicitly mentioned the challenges associated with building plants at scale, and discussed the degree to which the R&D amounts considered here would fund pilot plants (tens of MW in size) or demonstration plants (hundreds of MW in size). The R&D amounts we asked about ($250 m/year) were considered too small to fund demonstration plants directly, but at least one expert envisioned these amounts being used to fund pilot plants or partially fund demonstration plants, leading to more development. While it was recognized that monoethanolamine (MEA) was the most well known solvent, and would probably be used if a plant were built today, there was fairly wide agreement that to significantly reduce EP will require a breakthrough in solvents.

Adsorption. Most discussion was focused on materials research, with an emphasis on selectivity and longevity, but process improvements were mentioned also. The experts noted that adsorption works quite well at the lab bench scale, but there are serious questions about scaling it up at a reasonable cost.

Membranes. Multiple experts emphasized the tradeoffs involved in developing membrane technology, summarized as selectivity versus permeability. Given current technologies, a membrane that would separate CO_2 at a reasonable rate would be enormous. The technical hurdle most often mentioned is the pressure drop required and associated energy input. At least one expert noted that S2 would probably direct research toward more currently viable technologies rather than membranes.

Other PC. We deliberately left this category open in terms of definition. Two experts focused on algae and two experts focused on cryogenics as the most promising "other" post-combustion CC technology. A couple of experts who did not explicitly assess this category dismissed cryogenics as "brute force" chemical engineering where R&D is unlikely to have significant effect.

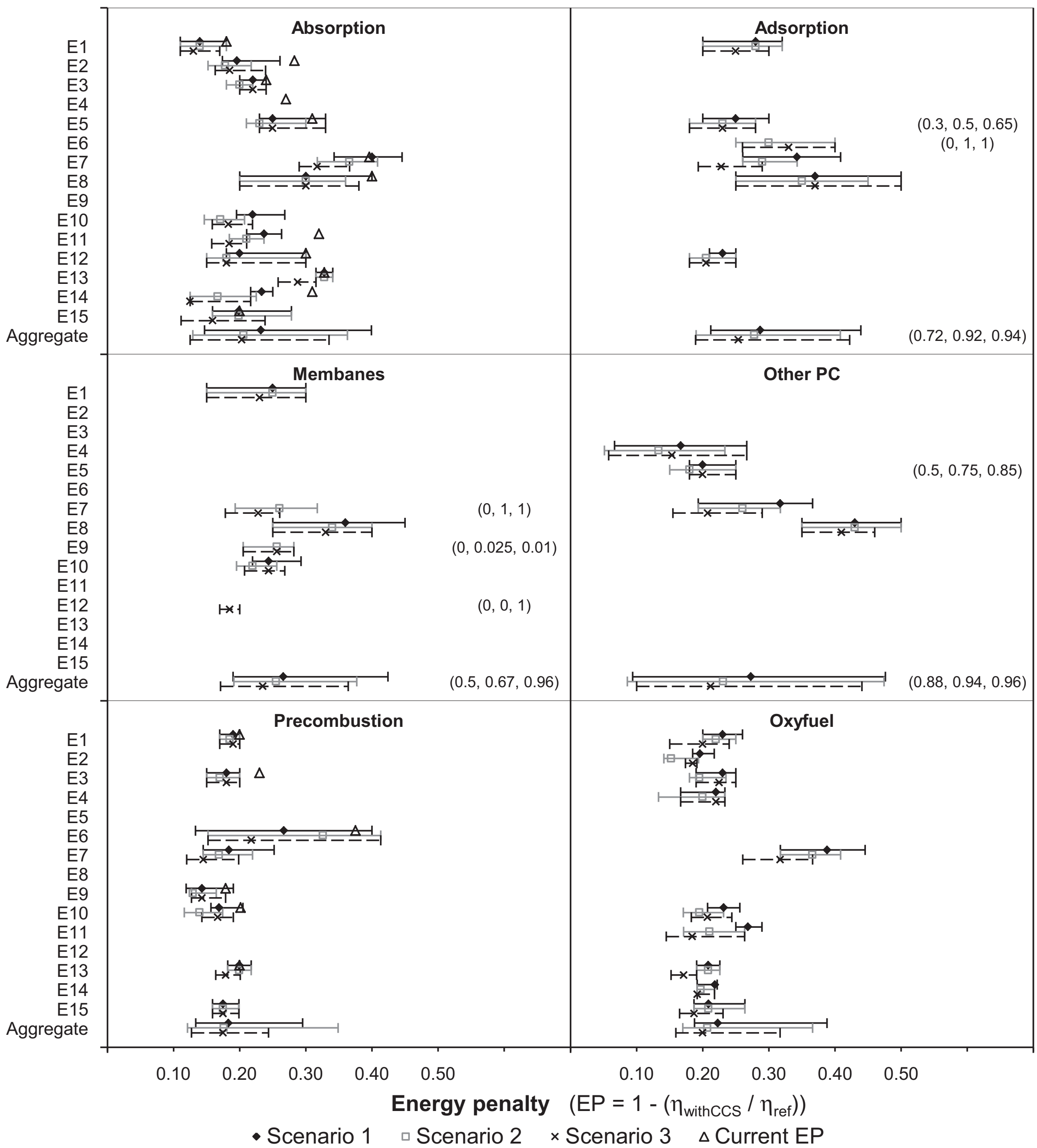

Fig. 1. Median and range (5th–95th percentile) of estimated energy penalty for each technology under each scenario, by expert and for the aggregated distribution.

Pre-combustion. Membranes, clean-up, and water–gas shift were the most commonly mentioned energy requirements, and thus the areas where improvements could reduce the EP. In particular, some experts felt that improvements in membranes might be amenable to R&D investments at this point, and multiple experts noted that gas separation technology is mature, and there is probably not much room for improvement. One expert said the “problem is not the capture, it's the IGCC.” For IGCC, multiple experts mentioned that the main technical challenge is in improving turbines, with one mentioning that turbines designed especially for IGCC might lead to significant improvements. It was felt that S2 may lead to building some IGCC plants, which would in turn lead to improvements in IGCC efficiency. Many experts felt, however, that the focus on IGCC is not, and will not, be in improving efficiency, but rather in reducing capital costs and improving reliability.

Oxyfuel. Experts mentioned that the focus on this technology may be improving the efficiency of the base plant, or reducing capital costs and increasing reliability, rather than reducing the energy required for oxygen production. Clean-up was mentioned as a particular problem, as oxyfuel results in an impure stream of CO_2. It was again mentioned that oxygen separation via membranes may be amenable to R&D at this point.

3.1.2. Qualitative description of the effects of policy scenarios

Several themes emerged during discussions of the scenarios with the experts. S1 was the easiest scenario for the experts to hypothesize and make estimates under, although they differed in how much work they thought would be done on each technology under this scenario. For technologies that are not yet well-developed, most felt that without further U.S. research and development funding, progress would essentially stop. For technologies that are more developed, some experts still felt that under S1 there would be no further development, and that the EP in 2025 would be very close to current estimates, while other experts

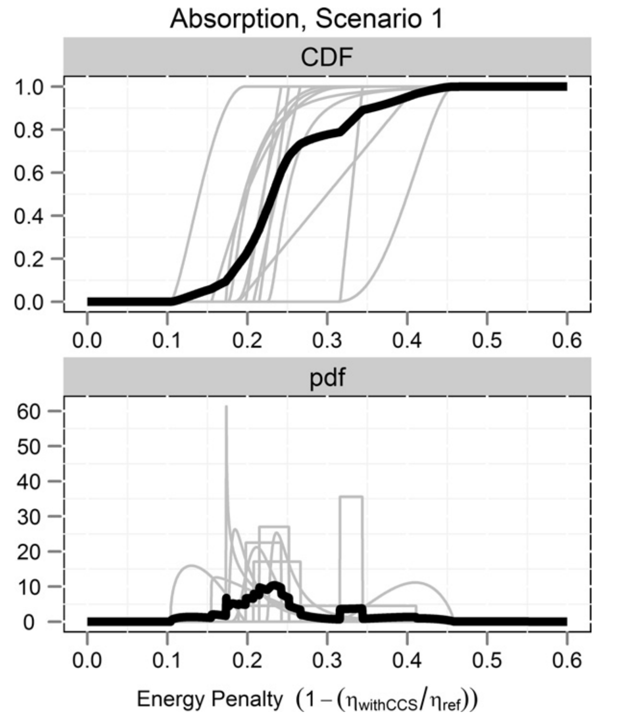

Fig. 2. Fitted probability distributions representing each of the individual expert assessments (gray lines) and the aggregated distribution (bold black line) for the energy penalty for absorption under Scenario 1.

suggested that development in other nations and some private sector development would continue to push the technologies forward, and that the EP in 2025 would most likely be lower than the current estimates for 2012. Opinions also varied on the effects of S2. Some felt that S2 would spur significant amounts of additional private investment in CC technologies, leading to relatively large improvements. Others estimated either no difference between S1 and S2 or only modest improvements, but gave very different rationales. One group of experts felt that even under current worldwide carbon policies (S1), private investment is already acting as if carbon pricing will occur (S2), and the other group of experts felt that the particular carbon price proposed in S2 was so high that it would drive other dramatic changes in the energy industry rather than driving improvements in CC technologies. This latter effect can be seen in the aggregated distributions: for pre-combustion, the 95th percentile EP estimate is higher for S2 than for S1. A majority of experts also offered a suggestion that any carbon pricing strategy be phased in rather than implemented in a single year as described in S2. The experts generally felt that increased research funding (S3) would lead to improvement in EP for all technologies, and, in aggregate, that those improvements would be slightly greater than the improvements from S2. Most experts, however, did not express much confidence in their judgments of how much increased funding would be necessary to spur technological advances.

3.2. Aggregated results

Each panel of Fig. 1 also shows the median and the 5th and 95th percentiles of the aggregated distribution, calculated as described by Eq. (2). Fig. 2 illustrates the aggregation: the fitted distribution representing each expert's individual assessment of the EP for absorption under S1 is shown, along with the calculated aggregate distribution. As shown, most experts' distributions lie predominantly between 0.15 and 0.25, but there are individual assessments that lie entirely below 0.15 and some that lie entirely above 0.35. Three experts estimated noticeably higher EPs than the others, resulting in the bimodal shape of the aggregate distribution clearly visible in the density function shown in the bottom panel. Similar bimodal aggregate distributions occur for all three scenarios for Other PC and oxyfuel (see the SM). The aggregate distributions for each technology under each scenario are right-skewed, meaning that, in aggregate, the experts believe there is some probability that the EP will turn out to be much higher than their best estimate, but that is more likely than the EP will turn out to be much lower. In several cases, experts described fundamental bounds below which EP could not fall.

4. Discussion

4.1. Differences across experts

A variety of differences among the experts' assessments can be seen in Fig. 1: there are relatively large between-expert differences in the estimated energy penalty for the post-combustion technologies, and some experts (e.g. E8) consistently expressed more uncertainty, as indicated by the difference between the 5th and 95th percentile, than others (e.g. E13). Still others (e.g. E1) expressed large uncertainty for some technologies and little uncertainty for others. With one exception, all experts estimated lower energy penalties under S2 and S3 than under S1 for every technology, often including lower estimates for all three assessed percentiles. In most cases the median estimate for S2 and for S3 lies within the 5th to 95th percentile range for S1, suggesting that while S2 and S3 make improvements in the EP more likely than under S1, those scenarios are not likely to lead to a breakthrough that could not occur in S1. In every case each expert's 5th–95th range for a technology included some overlap across the three scenarios.

For absorption and pre-combustion, we can compare the estimated EP in 2025 with the current EP as stated by the experts during their interviews. For all experts providing both estimates, the median EP in 2025 is less than their current EP value, and in some cases the entire assessed distribution lies below their current estimate (e.g. E2 for absorption). Most experts stated that it is possible that the EP in 2025 will be higher than current estimates, which can be seen from the comparison of the 95th percentile of their estimate of EP in 2025 to their current EP values. Across experts, the median S1 estimates for the EP for absorption ranged from 1% higher to 33% lower than their estimate of the current EP, and the estimated improvement was not correlated with their estimate of the current EP. For pre-combustion, the differences ranged from 0 to 29% lower, with the largest improvement estimated by the expert who gave the highest estimate of the current EP. These findings suggest that the differences in EP estimates across experts under S1 reflect more than just differences in their estimates of the current EP, for the two technologies where such comparisons are possible.

4.1.1. Uncertainty and individual contribution to variance

Given the large between-expert differences in assessments of some of the technologies, we were interested in exploring how much of the uncertainty in the aggregated distribution is due to uncertainty within the individual expert's distributions and how much is due to the difference between the experts' assessments. As shown in Eq. (2), the aggregate distribution is the equally-weighted sum of the individual distributions. Let x represent the aggregate distribution, i represent the individual distributions, w_i represent the weight on each distribution, and μ and σ^2 represent the mean and variance. Then σ_x^2, the variance of the aggregate distribution, is:

$$\sigma_x^2 = \sum_i w_i \sigma_i^2 + \sum_i w_i \times (\mu_i - \mu_x)^2 \quad (3)$$

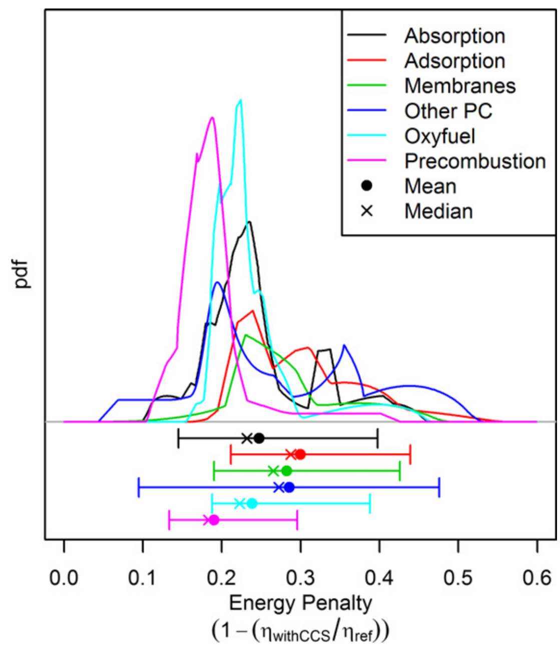

Fig. 3. Comparison of the aggregated assessments for energy penalty for each technology under Scenario 1.

The first term depends entirely on the variances in each individual expert's distribution, and the second depends on the difference between each expert and the average of all experts; we interpret the latter as the between-experts uncertainty. Table 2 summarizes the aggregate distributions for each technology, including the mean and variance (columns 4 and 5) of each aggregate distribution and the percentage of variance attributable to between-expert differences. The SM includes information on how to convert from the EP metric used here (the fractional decrease in net energy output per unit of energy input) to other EP metrics used in the literature. Across all technologies and scenarios, more than half of the variance in the aggregate distribution is attributed to differences between experts, indicating that (1) individual experts may be exhibiting overconfidence and (2) private knowledge about these technologies has not disseminated widely.

4.2. Differences across technologies

Fig. 3 compares the aggregate distributions for the six technologies under S1. Pre-combustion has both the lowest mean EP and the least uncertainty in that EP, followed by Oxyfuel and absorption. Adsorption has the highest mean EP, and Other PC has the largest uncertainty in EP, which is not surprising given its novelty and that it can encompass several technologies (e.g. some experts defined this as the use of algae, while others defined it as cryogenics). Also evident is the asymmetry of the distributions, with a long right tail indicating the possibility of EPs much higher than the mean estimate, similar to what was seen in Fig. 2. Similar patterns are observed for S2 and S3 (see the SM). While we identified EP as the most important technical factor to elicit, one should note in comparing technologies that other factors such as capital costs and process costs will also affect total costs of capture.

4.2.1. Sensitivity of mean EP to individual assessments

To explore further the impact of the differences in expert assessment on the comparison of technologies, we recalculated the aggregate distributions for EP using subsets of the experts (see detailed results in the SM). Not surprisingly, we found that the mean energy penalties for absorption, where we had the largest number of experts, were least sensitive to exclusion of individual experts. Excluding the highest individual result reduced the mean EP by 5.5% (from 0.248 to 0.234). The mean EP for precombustion and oxyfuel were also relatively insensitive, with maximum changes of 5.8% and 6.8%. The EP for Other PC is the most sensitive to individual experts, with exclusion of the expert with the highest EP reducing the mean EP by 19.9%, and exclusion of the expert with the lowest EP increasing the mean EP by 16.5%.

4.3. Differences across scenarios

Fig. 4 shows the effect of the different scenarios on the aggregate assessment results for each technology. These graphs show

Table 2
Mean and variance of the estimated energy penalty for each technology under each scenario, based on the aggregated distributions.

Technology	Scenario	Probability of technical viability based on 2025 technology[a]	Mean energy penalty[b]	Variance[b]	% of total variance attributed to between-expert differences
Absorption	1	1	0.248	0.0052	79%
Absorption	2	1	0.225	0.0054	81%
Absorption	3	1	0.216	0.0046	77%
Adsorption	1	0.72	0.3	0.0053	57%
Adsorption	2	0.92	0.282	0.0039	57%
Adsorption	3	0.94	0.273	0.0055	66%
Membranes	1	0.5	0.282	0.0049	56%
Membranes	2	0.67	0.264	0.0033	54%
Membranes	3	0.83	0.242	0.0021	50%
Other PC	1	0.88	0.286	0.0136	80%
Other PC	2	0.94	0.257	0.0146	87%
Other PC	3	0.96	0.248	0.0114	83%
Oxyfuel	1	1	0.238	0.0032	88%
Oxyfuel	2	1	0.221	0.0029	84%
Oxyfuel	3	1	0.211	0.0019	74%
Precombustion	1	1	0.19	0.0023	46%
Precombustion	2	1	0.188	0.0037	73%
Precombustion	3	1	0.178	0.0019	42%

[a] For some technologies, some experts either provided a probability of less than 1 or stated explicitly that the technology would not be developed or technically viable by 2025. Experts who provided estimates of the energy penalty with no such statement were assumed to believe that the technology would be technically viable by 2025. The probability shown in this column equally weights all experts stated or implied probability of viability.

[b] EP is characterized as the fractional decrease in energy output per unit of energy input. The values shown are the mean and variance of the aggregated distribution of EP for each technology/scenario combination. For technology/scenario combinations where the probability of technical viability is less than 1, the mean and variance shown are for the combined distribution conditioned on technological viability.

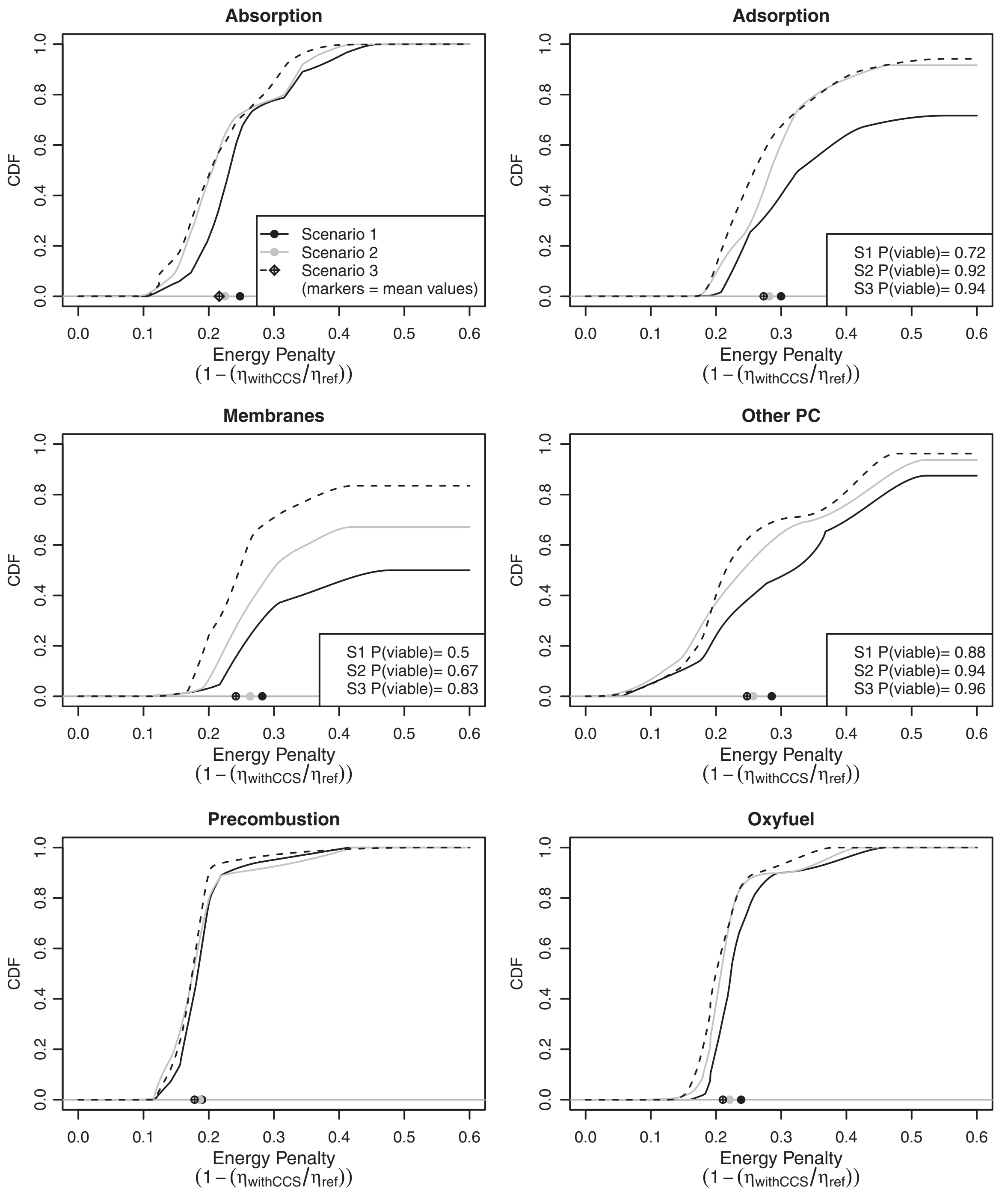

Fig. 4. Impact of carbon pricing (S2) or increased research funding (S3) on the aggregated EP distribution for all technologies.

the cumulative distribution functions (CDFs) of the aggregate distributions. For those technologies where the probability of viability by 2025 was less than 1, only the continuous portion of the aggregate distribution is shown, with the maximum cumulative probability equal to the probability of viability. For those three technologies, the effect of S2 and S3 on increasing the probability of viability is clear. For all technologies the aggregate mean EP is highest for S1. The mean EP for S2 is about 2 percentage points lower than under S1; the mean EP for S3 is 2–4 percentage points lower than for S1. These results imply that the experts believe all technologies would be promoted by a carbon tax and by increased research funding, and that for the levels defined in the scenarios, they felt that targeted research funding would be more effective at promoting the technology than changes in carbon policy alone. We can see that for adsorption and membranes, R&D notably increases the probability of viability and decreases the mean EP if the technology is technically viable, implying that experts see a possibility of a breakthrough. For pre-combustion and oxyfuel, S3 is more effective at reducing the chances of a poor outcome (high EP), as evident by the shift in the 95th percentiles of the distribution, than at increasing the chances of a very good outcome or much lower EPs.

To think about the potential for large improvements in EP, we look at the aggregate probability of viability, and at the 5th percentile of the distributions. We see that several of the technologies seem to show a substantial chance of a major improvement under

S2 or S3. For example, the aggregate probability that membranes will be a technically viable technology by 2025 increases from 50% in S1 to 67% (S2) or 83% (S3), and the probability of viability similarly increases for adsorption under S2 and S3. Within S1 (Fig. 3) and across scenarios (Fig. 4) Other PC shows a strong potential for low EP, with a 5th percentile EP of 0.09, as do absorption and pre-combustion, with 5th percentiles under S2 and S3 of 0.12 to 0.13. Other PC was generally considered to be the most speculative category, and only 4 experts responded, considering 2 different technologies. That this technology shows a chance of a breakthrough is not surprising – not much is known about this category, so there is a chance that it might outperform. Absorption and pre-combustion are more mature and were evaluated by a larger number of experts. While each show the potential for very low EPs at the 5th percentile, they also have lower mean and median EPs, so it may be possible to reach the lower EPs without the same level of fundamental breakthrough required for the less mature technologies.

5. Conclusions

In this study, we performed expert elicitations on the projected energy penalty for 6 different carbon capture technologies, under three different policy scenarios. The assessments presented in this paper suggest that (a) both of the policy instruments explored would likely lead to improvements in the EP for all of the CC technologies, at least at the levels studied here (b) at these levels, increased research funding is a more effective mechanism than carbon pricing for promoting the less mature technologies, and (c) the potential exists for several of the technologies (Other PC, absorption, and pre-combustion) to achieve EPs of 0.1–0.15 by 2025.

We found a large range of estimates across experts even in some of the most mature technologies. Several factors likely contribute to these differences: (a) a single capture technology will have different EPs for different base plants, (b) experts have differing beliefs about the EPs that will be seen in practice even for these more mature technologies, and (c) experts have differing beliefs about how much improvement will be seen in each scenario. Disagreement resulting from (a) could be reduced if experts were constrained to consider a single well-defined base plant, but such results would then not reflect the variability that is to be expected in deployed systems. Our results suggest that both (b) and (c) are relevant here, and we have made no effort to determine if one of these factors is more important than other. Disagreement from (b) or (c) could potentially be reduced by targeted efforts to share information, analyses, and the key challenges faced by each technology among CC experts. We note, however, that disagreement between experts is not uncommon (e.g. Morgan and Keith, 1995), and that even in elicitations that include efforts specifically aimed at determining and minimizing the sources of expert differences, disagreements can remain (Coppersmith et al., 2009).

We note here that the implications of these results for policy decisions also depend on combining the EP estimates with additional information to estimate the overall electricity and abatement costs. In particular, EP may not be the most important metric for some of the technologies, particularly pre-combustion, which depends heavily on the capital costs of IGCC, which are particularly uncertain. Stakeholder acceptance also affects feasibility of implementing CCS, and has been included in expert and public assessments (Sharp et al., 2009; Sala and Oltra, 2011).

Finally, because policy implications also depend on the economy-wide costs of the policies themselves they ultimately require comparing the costs of carbon pricing to those of R&D expenditures. Moreover, given some of the experts' qualitative responses, it seems possible that the types of improvements to EP via R&D will differ from those induced by carbon pricing, suggesting that there may be gains from implementing both policies simultaneously.

There are many ways to address climate change, including reducing emissions directly, spurring technical change to make emissions reductions less costly, and adaptation. When considering policies aimed at inducing technical change, there are a wide variety of technologies to consider, including CCS, energy efficiency technologies, renewable energy, nuclear, and geo-engineering. A pressing question is how to balance policies among all the different paths for addressing climate change, among categories of technologies when considering technology policies, and among specific sub-technologies. This research provides new perspectives on potential future reductions in CCS energy penalties, a significant contributor to the cost of CCS, which in turn is a critical factor in understanding how to design policies.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.ijggc.2012.11.022.

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