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**From Expert Elicitations
to Integrated
Assessment: Future
Prospects of Carbon
Capture Technologies**

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Summary

This paper analyzes the future prospects of carbon capture technologies. The first part of the analysis presents and discusses the results of an expert elicitation survey on a broad range of carbon capture options. The survey collected probabilistic estimates on the future values of energy penalty under three different scenarios of R&D investments and climate policies from twelve leading European experts from both academia and industry. In the second part of the analysis, the elicitation results are used as input to an integrated assessment model. This allows us to evaluate the potentials of success of this technology within a broad mitigation portfolio of options and under different policy assumptions, in an intertemporal optimizing setting. Both parts of the work provide results that are of interest to policy-makers, integrated-assessment and energy modelers.

Keywords: Carbon Capture, Expert Elicitation, Integrated Assessment Modeling

JEL Classification: Q5, Q55

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From expert elicitations to integrated assessment: future prospects of carbon capture technologies

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Abstract

This paper analyzes the future prospects of carbon capture technologies. The first part of the analysis presents and discusses the results of an expert elicitation survey on a broad range of carbon capture options. The survey collected probabilistic estimates on the future values of energy penalty under three different scenarios of R&D investments and climate policies from twelve leading European experts from both academia and industry. In the second part of the analysis, the elicitation results are used as input to an integrated assessment model. This allows us to evaluate the potentials of success of this technology within a broad mitigation portfolio of options and under different policy assumptions, in an intertemporal optimizing setting. Both parts of the work provide results that are of interest to policy-makers, integrated-assessment and energy modelers.

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1 Introduction

In a carbon constrained world, where the electricity generation sector is faced with having to address both fast growing demand and the need to reduce its greenhouse gas (GHG) emissions, carbon capture and storage (CCS) technologies are likely to play an important role (Bosetti et al, 2012a; Luderer et al., 2012).

Compared to other low-GHG energy production options, CCS may allow for a smoother transition towards a low carbon economy, by allowing the continued use of fossil fuels for the generation of electricity, at least in the short and medium term. It is considered a possible “bridge technology” that could be important while other low-carbon technologies are developed or enhanced. Contrary to other technological options, however, carbon capture and storage makes sense only in a carbon constrained world, and is not likely to be adopted otherwise.

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This paper focuses on the costs of carbon capture, which is one of the main obstacles to a widespread adoption of CCS. Social acceptability issues related to transport and storage, in addition to legal and long-term liability concerns, may also hinder its diffusion but are not considered within the present analysis. Transport and storage costs are much lower than those related to capture, and the availability of storage sites is not seen as a major issue (Gale, 2004; Hendriks et al, 2004; Holloway, 2005; IPCC, 2005).

Considering the wide range of energy technologies that could benefit from R&D investments and the limited nature of public funds, public investments in R&D for any of these technologies have high opportunity costs. It is therefore very important to evaluate the future prospects of these technologies in an integrated way. Our analysis contributes to this discussion in two ways. First, it investigates the expected efficiency achievements of six different carbon capture options by means of an expert elicitation survey developed in line with Jenni et al.(2013)⁵ to analyze the effectiveness of climate policies or R&D programs targeted at specific technologies, in terms of their impact on technological change. Second, it evaluates the attractiveness of CCS with respect to other electricity generation technologies by means of an integrated assessment model, which can provide quantitative and normative indications on the optimal strategies to undertake to reach specific climate stabilization targets.

There have been a number of elicitation studies on CCS in recent years (Baker et al., 2009a; Chan et al., 2011; Chung et al., 2011; National Research Council, 2007; Rao et al., 2006). Our study differs from these in two key aspects. First, we cover a large number of specific capture technologies, and find that efficiencies, costs and probabilities of success vary quite significantly. Second, we focus on technological parameters rather than cost parameters. The scientists and engineers who work on carbon capture are more knowledgeable about technical parameters, and cost parameters can be more easily modeled (Nemet and Baker, 2009). The study that is most similar to ours is Jenni et al. (2013). In fact, we share an elicitation protocol with this study. The key contribution of our study, with respect to Jenni et al. (2013) as well as all of the studies listed above, is that we focus on Europe, a very important player in the climate change debate and in the development and deployment of climate friendly technologies.

Furthermore, we analyze the impacts of the probabilistic outcomes in WITCH, an inter-temporal energy-climate model, to evaluate investments in CCS with respect to other technologies, given different climate policies. Rather than looking at CCS in a dichotomous way - considering it 'available' or 'not available' – as is common in the literature (see for example Kriegler et al, 2013 and Rogelj et al, 2013), we use the results of the expert elicitation to consider the impacts of a range of more plausible technological outcomes. Specifically, we consider three possible energy penalty evolution paths derived from the most pessimistic and optimistic experts. We find that evaluating different energy penalty paths does influence the costs of controlling climate change and the resulting mix of technologies.

⁵ In this paper we analyse a different sample based on mainly European experts.

The rest of the paper is structured as follows. Section 2 presents the methodology and the results of the expert elicitation. Section 3 presents the modeling tool and the assumptions made, and discusses the results of the simulation analysis based on the expert estimates of future carbon capture energy penalty. Section 4 summarizes the major findings of the paper and illustrates future research work.

2 Expert Elicitation

Policy-makers and researchers are increasingly recognizing the need to address uncertainty explicitly. The lack of data on uncertain processes and the interest and need to make projections concerning future technological developments in order to make informed R&D investment decisions has led to an increased use of expert judgments. Indeed, expert-informed opinions have been applied to assess risks and to support decision-making regarding many energy and climate-change related topics (Anadón et al., 2012; Baker et al., 2009a; Baker et al., 2009b; Bosetti et al., 2012b; Bosetti et al., 2012c; Cooke, 1991; Cooke and Goossens, 1999; Chan et al., 2011; Hogarth, 1980; Jenni et al., 2013; Morgan and Henrion 1990).

2.1 The elicitation protocol

The aim of our survey is to assess the future technical developments of six technological approaches to carbon capture applied to power plants. More specifically, as in Jenni et al. (2013), we focus on four post-combustion technologies - including absorption or solvents, adsorption, membranes and ionic liquids, and other post-combustion technologies - one pre-combustion technology, and one alternative capture technology, oxyfuel (Table 1). These technologies were chosen because they provide a reasonable representation of carbon capture technologies at different current levels of development. All of the technologies may benefit from further research and technical improvements.

Post-combustion	Pre-combustion	Alternative combustion
Absorption / Solvents Adsorption Membranes and Ionic liquids Other post-combustion technologies (e.g., enzymes or cryogenics)	Pre-combustion capture	Oxyfuels

Table 1: Carbon capture technologies included in the elicitation.

We gathered expert judgments on future values of energy penalty (EP), which we define as the energy required to capture and compress CO₂ from a power plant, to evaluate how each of the six technologies will be affected by climate policy or by EU publicly-funded R&D programs. Literature on expert elicitation shows how important the design of the survey is for obtaining reliable data, as experts can be subject to cognitive and motivational biases (Clemen and Reilly, 2001; Keeney and von Winterfeldt, 1991; Meyer and

Booker, 1991; Morgan and Henrion, 1990; O'Hagan et al., 2006; Phillips, 1999; Walls and Quigley, 2001). The way in which the survey is conducted can also play a major role in the accuracy and quality of the data collected (Bowling, 2005). Finally the choice of the experts is also a crucial part of the elicitation as the quality of the data depends on the expert's technical background, knowledge, and ability to reason in probabilistic terms (O'Hagan et al., 2006).

The elicitation method used for this analysis was a self-administered web-survey with graphical devices, with a follow-up interview by telephone. The surveys were carried out between December 2011 and May 2012, after an initial pre-test with a few experts to ensure the clarity of the questions. A list of leading scientists working on carbon capture within institutions, academia or industry was prepared. Each expert was contacted via email and invited to take part in the survey, after having received an explanation of the project aim. After acceptance, the link to the web survey was sent. The double contact procedure via email was intended to set up a communication channel with the expert and to increase the probability the experts would complete the survey.

Most of the expert elicitation literature suggests the use of in-person interviews, which were used in Jenni et al. (2013). Web survey approaches are becoming more common (Lindhjem and Navrud, 2011), although literature lacks a thorough comparison of the different survey modes for expert elicitations.

Our decision to use a web survey was based on the aims of: *i*) trying to get broad expert participation, by reaching each expert independently of their location and schedule; *ii*) allowing experts flexibility in how and when they responded, by providing the opportunity to use multiple sessions and to access additional material while answering, if desired; and *iii*) providing real-time visualization support, by accompanying quantitative survey responses with live graphical displays. Web surveys also dramatically reduce the costs of the data collection and may avoid some biases related to the interviewer and to a lower level of anonymity. On the other hand, there might be issues of satisficing, i.e., shortcutting the response process or not stimulating motivation (Krosnick, 1991; Simon, 1956). To counteract this, we organized a round of follow-up telephone interviews to check the elicited information, to deepen the discussion with each of the experts, and, when necessary, to correct for possible inconsistencies and to check the appropriate interpretation of the questions and/or answers.

The questionnaire was organized in six sections, one for each subset of technologies. We asked experts to consider all possible technologies that may fall under each category and to focus on the technological potential, in terms of the estimated EP for each technology based on those technologies in 2025, but not on whether the technology will be fully commercialized by then. Experts were asked to provide their estimates for the EP⁶ for each technology in 2025. We asked them to give us a high, median, and low estimate of the EP for each

⁶ Experts reported their estimates in terms of the energy penalty metric that made sense to them; choosing among 4 metrics - specified in the Appendix - shared with Jenni et al. (2013), or choosing their own formulation.

technology for each scenario (corresponding to the 95th, 50th and 5th percentiles).

The specific scenarios we asked experts to consider are:

- Scenario 1 (S1): No further R&D for the specific capture technology is funded by the EU, and there are no changes in current carbon policies worldwide. However, there may be additional private R&D funding in the EU and both private and public funding in other regions of the world.
- Scenario 2 (S2): No further R&D for the specific capture technology is funded by the EU, but some type of carbon price is enacted worldwide, beginning in 2015. Assume that whatever form the policy takes, it has the effect of about a \$100 /ton of CO₂ Carbon Tax worldwide.
- Scenario 3 (S3): Assume that the EU increases investments in the specific capture technology R&D substantially, to about \$250 million per year, starting in 2015 and continuing at that level through to 2025. Assume that there is no carbon pricing implemented - current worldwide CO₂ policies remain in place.

As a reference, we also provided information on the level of investments of the last ten years: since 2002 annual R&D investments for capture technologies in the EU have ranged between 0.6-111.0 Million 2010US\$, with an average of 41.6 Million 2010US\$.

Twelve experts took part in our analysis organized in 10 single surveys and one two-person team; their names and the affiliations are reported in Table 2 in alphabetical order, and their answers are anonymously reported in Section 2.2. Six of the 12 experts are from Italy, and the sample is otherwise balanced, with 55% of experts coming from research centers or academia, and 45% from industry.

Name	Affiliation	Country
Michiel Carbo	Energy research Centre of the Netherlands	The Netherlands
Umberto Desideri	Università di Perugia	Italy
Jan Wilco Dijkstra	Energy research Centre of the Netherlands	The Netherlands
Jim Dooley	Pacific Northwest National Laboratory	USA
Stefano Malloggi	Enel	Italy
Gianpaolo Manzolini	Politecnico di Milano	Italy
Ivano Miracca	Saipem	Italy
Arno Neveling	Sasol	South Africa
Alberto Pettinau	Società Tecnologie Avanzate Carbone - Sotacarbo	Italy
Nils Rokke	SINTEF	Norway
Gianluca Valenti	Politecnico di Milano	Italy
Ron Zevenhoven	Abo Akademi University	Finland

Table 2: List of experts taking part in the survey.

2.2 Survey results

The survey was designed to elicit subjective estimates of the probability distributions of the EP induced by carbon capture technologies on thermal power plants in 2025, and to evaluate how the EP distribution would be

affected by changes in climate policy or in the EU public energy R&D strategy. We asked each expert to give us a high, median and low estimate of what the EP for each carbon capture technology could be in 2025 under the three different policy scenarios shown above. We defined these to correspond to the 95th, 50th, and 5th percentile of the experts subjective distributions. The answers to these questions are reported in Figure 1. Each panel refers to a specific technology. Within the panels, each line reports the estimates provided by the corresponding expert - with the central value identified by a symbol and the low and high values (5th and 95th percentiles) by the whiskers. The last line of each panel reports the percentiles of the aggregated probability distribution derived by combining the answers by all experts as detailed below. The three colors refer to the three policy scenarios. To improve comparability, the EP values reported by the respondents have been all translated into the following metric:

$$EP_1 = 1 - \frac{\eta_{withCCS}}{\eta_{ref}} \quad (1)$$

where η_{ref} is the efficiency of the reference plant without carbon capture, and η_{ccs} the efficiency with carbon capture.

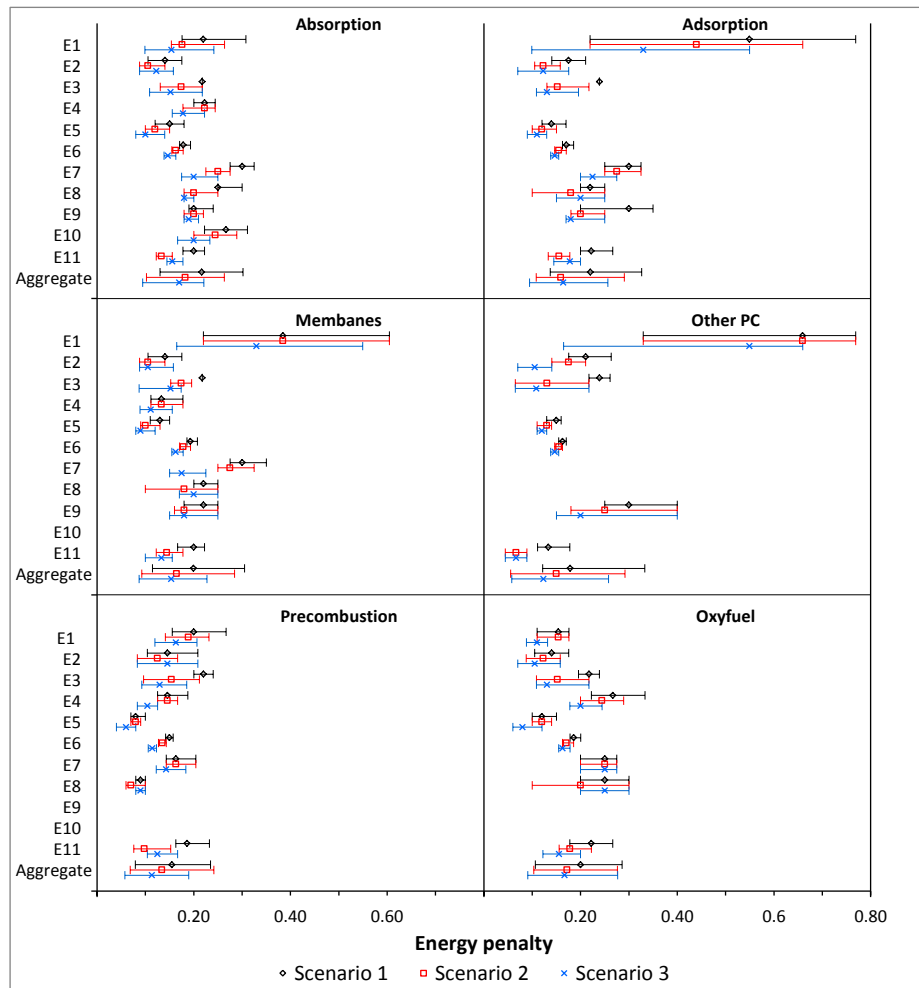


Figure 1: Expert estimates 5th, 50th, 95th percentiles EP in 2025. Panels refer to technologies and colors to scenarios.

By 2025, under S1 – No further publicly-funded R&D plus current worldwide carbon policies -- experts expect the EP of carbon capture to lie somewhere between 0.08 and 0.659 (minimum and maximum of the median values provided by the experts across all six technologies). The high end of this range is driven by one expert (E1) who expressed very high energy penalties for three of the technologies. The follow up interview with Expert E1 led to small modifications in some estimates, and an explanation for the relatively high values: these estimates were based in part on his conviction that adsorption, membranes and other post-combustion technologies have a low probability of being technically feasible by 2025, and even if they are technically feasible, the energy penalties could be very large. Although the full range is large, most of the median EP estimates are between 0.15 and 0.24, with a midpoint of 0.20 under S1 (the median of the median estimates across all experts and all technologies).

Under S2 – no further publicly funded R&D plus \$100/ton CO₂ tax – the estimates for the EP decrease for almost all experts, with the midpoint of the median estimates at 0.163.

If we look at the answers for scenario S3 – increased publicly-funded R&D investments plus current worldwide carbon policies – we find that the estimates for the EP are typically lower than for the other two scenarios, and the midpoint of the median value is 0.147 across all experts and all technologies. In general, we find that the subjective values for the 50th percentile are consistently lower when moving from scenario S1 to scenario S2 or S3, as it would be expected. The reduction in EP from scenario S1 to scenario S2 - due to the imposition of the a \$100/ton CO₂ price to carbon emissions tax - ranges from 0 to 50% depending on the expert and on the technology; while from S1 to S3 - due to increased publicly-funded R&D investments – the EP reduction ranges from 0 to 55%. Averaging the reduction in the median EP values between scenarios across all experts for each individual technology yields the values reported in Table 3.

Technology	% change S1 to S2	% change S1 to S3	% change S2 to S3
Absorption	-16%	-23%	-8%
Adsorption	-22%	-27%	-6%
Membranes	-15%	-23%	-10%
Other post-comb.	-21%	-33%	-15%
Pre-combustion	-14%	-20%	-4%
Oxyfuels	-11%	-22%	-11%

Table 3: Average change in the median estimated EP across scenarios, for each technology.

A similar reduction in the estimated EP arises when moving from scenario S2 to scenario S3, suggesting that even a significant carbon tax may have less effect - in most of our experts opinions - than a subsidy to carbon capture R&D (the increase in R&D considered was consistent with (Jenni et al. 2013)).

The two technologies with the greatest uncertainty, as measured by the difference between the 5th and 95th percentiles and coefficient of variation, are adsorption and other post-combustion.

Uncertainty increases from scenario S2 to S3, possibly indicating that the impact of public R&D could be more uncertain than private initiatives led by a climate policy.

We use the elicitation results to estimate probability distributions over EP for the different carbon capture technologies in 2025 for each expert by fitting distributions to their assessed 5th, 50th and 95th percentiles. We then aggregate the distributions of each expert using a linear opinion pool approach with equal weights (Clemen and Winkler, 1999), as in Jenni et al. (2013). Aggregated distributions such as these are examples of a commonly-used output of expert elicitation studies. Results are presented as cumulative distribution functions in Figure 2. Curves that do not reach a cumulative probability of 1 indicate technologies that at least one expert estimated might not be technically feasible: adsorption, membranes, and other post-combustion. The maximum value of those curves indicate the aggregated probability of technical feasibility across the 12 experts.

The fact that our elicitation survey shares a large part of its protocol with Jenni et al. (2013) - i.e., the selected technologies, the wording and structure of the main questions, and the evaluated scenarios - allows us to compare results across both studies. We find that most EP estimates in Jenni et al. (2013) also

range between 0.15 and 0.25. As in our study, a few experts present very large ranges between the 5th and 95th percentile estimates, especially for specific technologies (adsorption, membranes and other post-combustion technologies) considered less mature, highlighting the uncertainty around the possible future outcomes. In both studies, both global carbon pricing policies and increased R&D funding are estimated to achieve lower EPs, and this effect seems to be slightly higher for the scenario with increased R&D funding (S3) than for the climate policy scenario (S2). A difference across the two studies is that the effect of S2 is apparently larger in our elicitation. In particular, while in Jenni et al. (2013) the median EPs for S2 and S3 lie within the S1 interquartile range for most experts for most technologies, this is true for less than 60% of the expert estimates in our study. This suggests that our experts are more inclined to consider carbon policy measures as means for achieving technological breakthroughs that could not be achieved otherwise (S1).

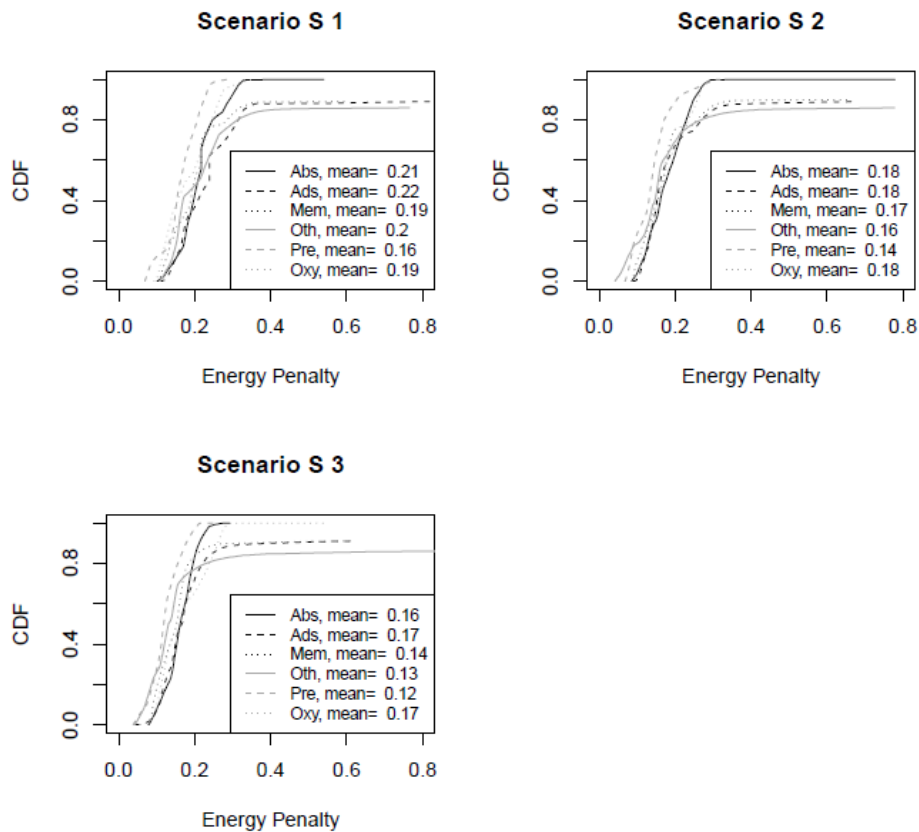


Figure 2: Aggregated cumulative distribution functions and mean value for the EP of each carbon capture technology resulting from the elicitation surveys, for each policy scenario.

On the basis of the distribution functions in Figure 2, which are comparable with those reported in Jenni et al. (2013), we can identify a ranking of technologies in terms of estimated EPs in 2025 and compare the results among the two studies. Figure 3 shows, for each scenario, such a comparison on the basis of the 5th, 50th, and 95th percentiles of the aggregated distributions. While

in some cases the most relevant element for policy makers or analysts may be the central values - for example, when elicitation is used to calibrate a model using the median or mean of a distribution -, the rankings by 5th and 95th percentiles might be of interest if the key study questions have to do with the likelihood of reaching very low or very high values, rather than the central tendency.

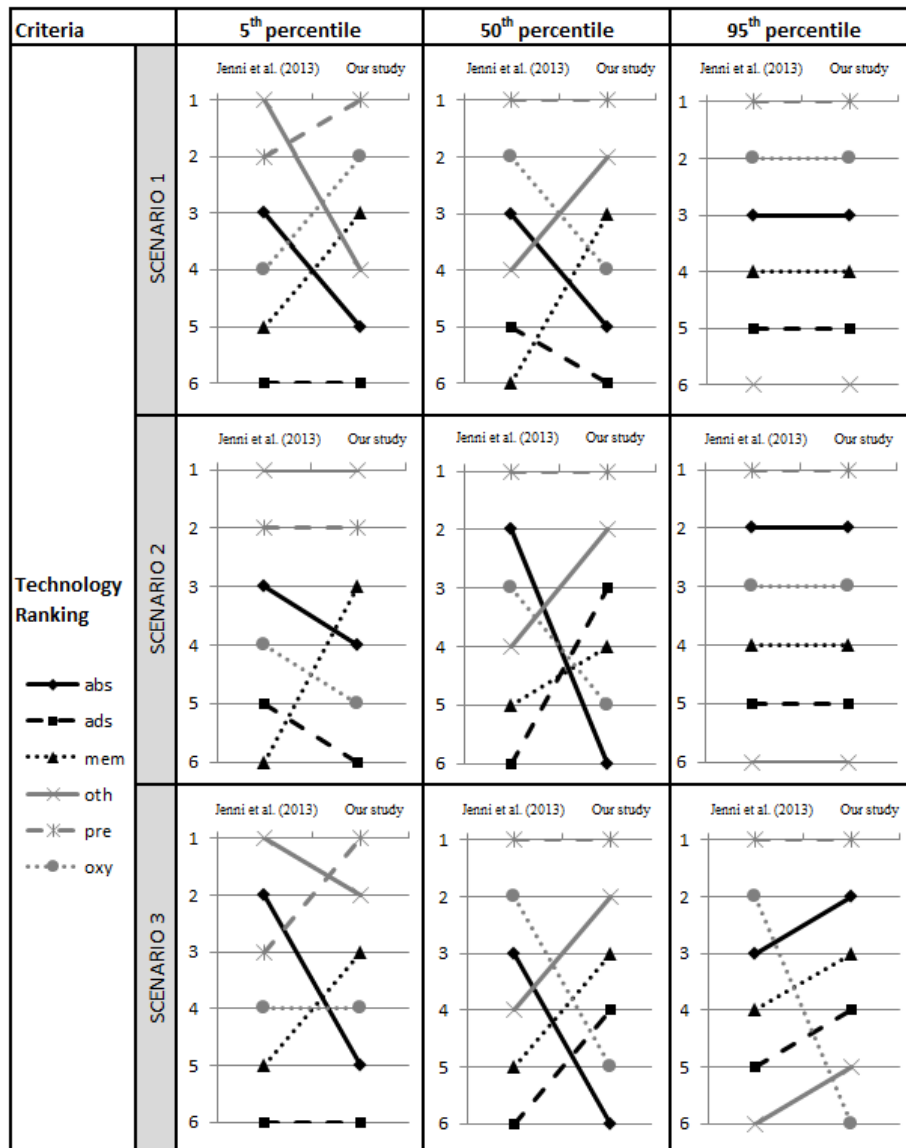


Figure 3: Comparison of technology rankings by elicitation mode, for three scenarios and three ranking indices.

Looking at the central values, the most promising technology seems to be ‘pre-combustion’ for both studies and all three scenarios. If instead we focus on the 5th percentile, and therefore on possible breakthrough events, the two most promising technologies are ‘other post-combustion technologies’ and

‘pre-combustion,’ each of which ranks either first or second in at least one of the two studies for all three scenarios. ‘Other post-combustion technologies’ is also the worst performing technology when focusing on the worst possible outcome (95th percentile), which is consistent with the much greater uncertainty in the estimated performance of this “bundle” of technologies, all of which are quite immature.

3 CCS as a climate change mitigation strategy

While the elicitation gives us information about the relative efficacy of R&D investment into different technology categories, it does not shed light on the importance of advancements in CCS in the economy; for that we turn to an integrated assessment model. The results of this elicitation form the basis for our choices for the EP development paths that are tested in the integrated assessment model.

3.1 The WITCH Model

WITCH - World Induced Technical Change Hybrid - is a regional integrated assessment model structured to provide normative information on the optimal responses of world economies to climate policies (Bosetti et al. 2006, 2007). It is a hybrid model that combines features of both top down and bottom up modeling: the top-down component consists of an inter-temporal optimal growth model in which the energy input of the aggregate production function has been integrated into a bottom-up description of the energy sector.

WITCH’s top down framework guarantees a coherent, fully intertemporal allocation of investments, including those in the energy sector.

On the basis of geographic, economic and technological vicinity, world countries are aggregated into thirteen regions that interact strategically on global externalities: GHGs, technological spillovers, and a common pool of exhaustible natural resources⁷.

WITCH contains a representation of the energy sector which allows the model to produce a reasonable characterization of future energy and technological scenarios and an assessment of their compatibility with the goal of stabilizing greenhouse gases concentrations. In addition, by endogenously modeling fuel prices (oil, coal, natural gas, uranium), as well as the cost of storing the CO₂ captured, the model can be used to evaluate the implication of mitigation policies on the energy system in all its components.

In WITCH, emissions arise from fossil fuels used in the energy sector and from land use changes that release carbon sequestered in biomasses and soils.

Emissions of CH₄, N₂O, SLF (short-lived fluorinated gases), LLF (long-lived fluorinated) are identified, as well as emissions of SO₂ aerosols, which have a

⁷ The regions are USA, WEURO (Western Europe), EEURO (Eastern Europe), KOSAU (South Korea, the Republic of South Africa and Australia), CAJAZ (Canada, Japan and New Zealand), TE (Transition Economies), MENA (Middle East and South Africa), SSA (Sub-Saharan Africa except the Republic of South Africa), SASIA (South Asia), EASIA (South-East Asia), CHINA, LACA (Latin America and the Caribbean), INDIA.

cooling effect on temperature. Since most of these gases arise from agricultural practices, the modeling relies on estimates for reference emissions, and a top-down approach for mitigation supply curves⁸.

A climate module governs the accumulation of emissions in the atmosphere and the temperature response to growing GHG concentrations. WITCH is also equipped with a damage function that provides the feedback on the economy of global warming. However, in this study we exclude this climate damage feedback and we take the so-called “cost-effective” approach: given a target in terms of GHG concentrations in the atmosphere, the model produces projections that minimize the cost of achieving this target.

Endogenous technological dynamics are a key feature of WITCH. Dedicated R&D investments increase the knowledge stock that governs energy efficiency. Learning-by-doing curves are used to model cost dynamics for specific technologies. Both energy-efficiency R&D and learning exhibit international spillovers. Two backstop technologies - one in the electricity sector and the other in the non-electricity sector - necessitate dedicated innovation investments to become competitive.

The base year for calibration is 2005; all monetary values are in constant 2005 USD. The WITCH model uses market exchange rates for international income comparisons.

3.2 Modeling assumptions and scenarios

The core of our work is to assess whether, and under what conditions, carbon capture and storage would become an important contributor to climate change mitigation. To do so, we run a series of deterministic scenarios to explore the solution space. Table 4 presents the combinations of policy and CCS EP scenarios (based on the elicited numbers) that are analyzed, reporting the abbreviations used to indicate the different simulations.

⁸ The mitigation supply curves include the assumption that reducing emissions from deforestation and degradation (REDD) is estimated to offer sizeable low-cost abatement potential. WITCH includes a baseline projection of land use CO₂ emissions, as well as estimates of the global potential and costs for reducing emissions from deforestation, assuming that all tropical forest nations can join an emission trading system and have the capacity to implement REDD programs.

		CCS SCENARIOS	
		Worst _t	Best _t
	(Policy in 2015-2025)	(Policy post-2025)	
POLICY	S1	No climate policy	S1 -bau-w (EP ₂₀₂₅ =0.27)
	S1	Stab 450	S1 -w (EP ₂₀₂₅ =0.27) S1-b (EP ₂₀₂₅ =0.08)
	S2	Stab 450	S2-w (EP ₂₀₂₅ =0.24) S2-b (EP ₂₀₂₅ =0.07)
	S3	Stab 450	S3-w (EP ₂₀₂₅ =0.20) S3-b (EP ₂₀₂₅ =0.06)

Notes: S1 = No further publicly-funded R&D/current worldwide carbon policies; S2 = No further publicly funded R&D/world-wide carbon policy equivalent to \$100/ton CO2 tax; S3 =Increased publicly-funded R&D investments/current worldwide carbon policies; Stab 450 = worldwide cap and trade mechanism to reach a 450 ppm CO₂-eq target; worst = EP equal to the median estimate of the least optimistic expert under the corresponding S_t scenario; best = EP equal to the median estimate of the most optimistic expert under the corresponding S_t scenario.

Table 4: Summary of the different policies and EP scenarios analyzed.

We simulate three possible short-term policies for 2015-2025, in accordance with the elicitation survey scenarios S1, S2 and S3. After 2025, we assume that a global long term policy is enforced (either no policy or stabilization at 450ppm). In addition, after 2025 we consider two different realizations for the value of CCS EP, a best and a worst, which we discuss below. The 450ppm policy is meant to reach the 2°C over pre-industrial global mean temperature target with a probability of 75% and is implemented assuming the efficient intertemporal and across regions allocation. This is far from being the most likely outcome of political negotiations on climate change, but in the context of this paper we focus only on the relative change in costs and investments due to different EP realizations and scenarios, rather than absolute regional costs.

The S1 policy is simulated by assuming business as usual and no additional R&D funding. We then have two cases following this policy, a “no climate policy” baseline, and a 450ppm stabilization policy. The EP values for both of these cases are based on the results of the survey for S1. Although the overall efficiency of the underlying power plants changes over time, we assume that the EP of CCS remains constant after 2025. Consistent with the definition of the S2 scenario in the elicitation, the S2 scenario in WITCH was implemented by establishing a global emissions cap-and-trade policy that is roughly equivalent in effect to a \$100ton/CO₂ carbon tax.⁹

The S3 policy is simulated assuming business as usual in the near-term, while subsidizing R&D in carbon capture. This is modeled by assuming costs are financed publicly and diverted from overall investments. The short term scenario is then again followed by a 450ppm policy.

These policy scenarios are further combined with technology scenarios about the possible future outcomes of carbon capture energy penalties. In particular, for each of the short term policy scenarios (S1, S2, S3) we define two EP scenarios. We select the least (‘Worst’) and most (‘Best’) optimistic experts associated with that short-term policy scenario. To define “best” and “worst” EP estimates for each short term scenario, we first identified the best

⁹ The choice of a quantity mechanism versus a price mechanism is related to the fact that in order to compare all different scenarios in terms of costs we want their cumulated environmental performance to be the same.

performing technology for each expert, based on the median EP estimates. We then select the lowest median EP as the “best” EP, representing the opinion of an “optimistic” expert, and the highest median EP as the “worst” value, representing the opinion of a “pessimistic” expert¹⁰ (see Anadon et al 2011 for an example of a similar approach). The specific values are given in Table 4. We incorporate the EP data in the simulation model, allowing carbon capture to be applied to coal, gas and woody-biomass fired power plants. We assume a capture efficiency of 90%, in line with current technological predictions, making this technology low carbon, but not completely carbon-free. Note that for S2, CCS technologies might be profitable earlier than 2025 and an assumption of what the EP value would be for these earlier periods is required. We assumed EP would be the 95th percentile of the distribution of the expert (either optimistic or pessimistic) that the 2025 EP value is based upon. After 2025 the 450ppm policy is enforced.

3.3 Modeling results

The focus of our modeling exercise is the role of carbon capture and storage, conditional on the EP estimates we elicited from experts. We compare scenarios focusing on the role of CCS in the power sector and the implications for climate policy costs. We consider three different aspects of scenarios: (1) the direct impact of the short term policy, i.e. inaction, a price on carbon, a subsidy to R&D; (2) their indirect impact through the effect on EP; (3) the implication of optimistic versus pessimistic assumptions about EP. As it would be expected, the presence of a price on carbon is a necessary condition to see any deployment of CCS. The presence of additional public funding for carbon capture R&D without any changes to current worldwide carbon policies (S3), is not sufficient to justify CCS investments prior 2025, even when a climate policy is foreseen for the successive periods. On the other hand, the implementation of a short term carbon pricing policy at the level of \$100/ton CO₂ (S2) does trigger electricity generation with CCS as early as 2020.

¹⁰ To further test our results, we also tested extreme scenarios considering the worst central estimate given by any expert across all technologies. In this case, the EP values are 0.66 for S1 and S2 and 0.55 for S3.

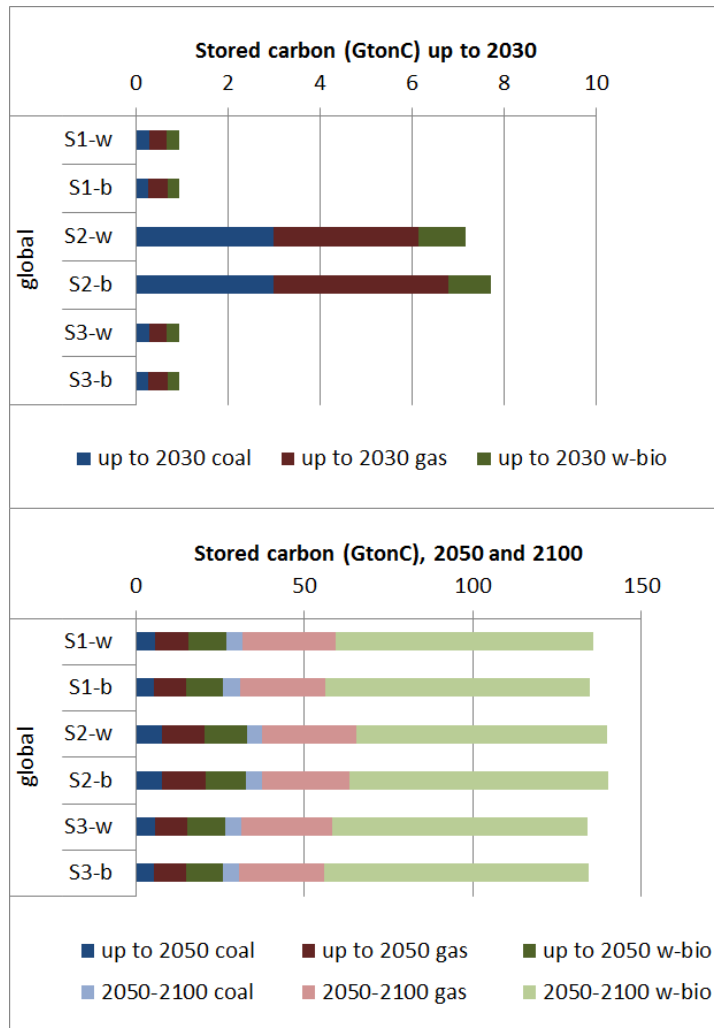


Figure 4: Cumulative captured carbon under all scenarios for the three electricity generation technologies that are coupled with CCS in the model. The upper panel reports the cumulative captured carbon up to 2030. The lower panel reports in darker colors the cumulative values up to 2050, while in lighter colors the additional captured carbon from 2051 to 2100.

In the short term (upper panel of Figure 4) we see that when CCS does play a visible role (in S2), the EP realization has an impact on both the extent of the technology penetration as well as the type of power plant it is combined with. More CCS is adopted under the best outcome of the EP realization, S2–b, and the increase comes from more deployment in gas-fired plants. While there is more CCS overall in the best outcome, there is a slightly larger amount of CCS with bioenergy under the worse realization of EP. Indeed, if we look at even higher EP (the worst median among all technologies) we see that the portfolio is dominated by biomass rather than gas (Figure 5).

In the longer term (lower panel of Figure 4), we also see a slightly greater penetration of bioenergy when the EP for carbon capture is higher. However, differences are relatively minor, as the role of bioenergy coupled with CCS is

so key to the decarbonization of the economy that neither differences in short term policies nor differences in the CCS EP end up having much impact on the total amount of carbon that is captured.

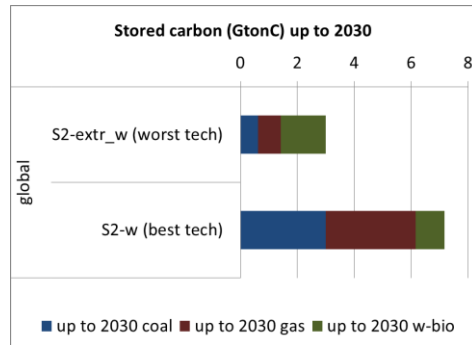


Figure 5: Cumulative captured carbon up to 2030 under two possible definitions of worst EP realization for the three electricity generation technologies that are coupled with CCS in the model. The upper bar reports the cumulative captured carbon considering the worst central estimate of EP given by any expert for any technology. The lower bar reports the cumulative values for the least optimistic expert as described above.

Over the whole century, gas and woody-biomass fueled power plants dominate, regardless of the short term policy scenario or the EP realization. In the presence of a short-term policy (S2 and S3 scenarios) slightly more total carbon is stored when the EP is low than when it is high. However, for the S1 scenarios we see the reverse, with more total carbon stored under a high EP than a low EP. S1-w has the worst realization of EP across all scenarios, and a higher EP means that it takes more fuel to generate the same amount of electricity; hence more carbon is stored to meet the same goal. Indeed, in the longer term as the stabilization target becomes an increasingly daunting task, the main driving mechanism becomes the cost of carbon. This in turn entails higher costs in the very long run. However, when we look at the impact on policy costs, shown in Figure 6, we see that unless mitigation costs borne in the future are not discounted (i.e., the top graph reporting undiscounted cumulated costs), the short term policy has a larger impact on policy costs than does the difference in CCS energy penalty.

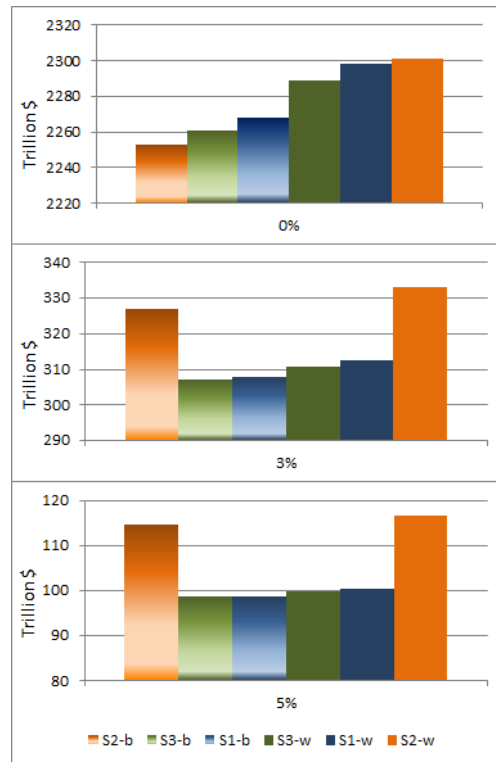


Figure 6: Global cumulated GDP losses under different policy scenarios with respect to the business as usual scenario for different discount rates, 0% , 3% and 5% (scenarios sorted in order of increasing losses under the 0% discount case)

Within a policy scenario, the low EP cases always entail policy costs that are between 1 to 2% lower than those under high EP cases, regardless of discount rate or short term scenario.

If we ignore the time dimension of costs and we simply look at cumulative undiscounted costs (upper panel in Figure 6), then a low EP and scenario S2 - no further publicly funded R&D plus \$100/ton CO₂ tax- leads to the lowest costs. Earlier investments in decarbonizing the economy are matched by lower effort later in the century. With a high EP, this dynamic advantage is not pivotal anymore, as the preferred short term action would be S3, increased R&D funding alone.

As we consider discounted policy cost metrics (central and bottom panel of Figure 5) the near-term costs of S2 start to overwhelm the longer term cost savings, and other scenarios lead to lower total discounted costs – in particular, S3 becomes the most robust short term policy choice as it dominates (although just marginally in some instances) both the other two options for both low and high EP cases.

4 Conclusions and future developments

We use structured expert judgments to assess the future efficiency of carbon capture technologies for coal, gas and woody-biomass based power generation.

We present the estimates of 12 leading (mainly European) experts elicited via a web-survey followed in some cases by telephone follow-up interviews. The elicitation yields results for three scenarios, each characterized by different levels of climate and technology policies and R&D investments, and is aimed at identifying probabilistic projections of EP for six different carbon capture technologies in 2025. Our results suggest that, given current worldwide carbon policies, the most promising technology for carbon capture (in terms of the lowest EP) is pre-combustion capture; the technologies with the least potential are adsorption and absorption; and the technologies most likely to have very high EPs are ‘other post combustion’ (a bundle of technologies that includes enzymes and cryogenics), membranes, and adsorption. With a carbon policy, we find that ‘other post combustion’ has the greatest uncertainty, including both the possibility that it will be the best performing technology and the possibility that it will be the worst performing technology.

Energy penalties in 2025 are foreseen to range from 0.08 to 0.66 if we focus on the central estimates of the experts in our sample, or from 0.04 to 0.77 if we look at the full assessed range (the 5th to 95th percentiles) of all experts across all technologies and all scenarios. The high variability of such estimates clearly highlights the importance of investigating the potential for the different available technologies under different future policy decisions, as was done in this study, as such values imply different near and longer terms adoption profiles for the technology, as well as different policy cost implications. In terms of the effectiveness of different policy scenarios, experts consistently assess increased public R&D funding as having a greater impact on EP than market mechanisms, but with a greater spread. This may be related to the opinion that public funding could be more targeted towards the less mature technologies, and therefore with more uncertain outcomes. Both policy scenarios significantly lower the experts’ median estimates for EP in 2025, on average by between 11% and 33% depending on the technology; the scenario with increased R&D funding is on average an additional 4% to 15% below the carbon policy.

In the second part of the analysis, we derive from the web-survey data two EP paths for each short term policy scenario, selecting an optimistic (“best”) and pessimistic (“worst”) EP value, and incorporate such results into an integrated assessment model, the WITCH model. The model allows us to use the elicited data within a broader framework that accounts for other, competing, mitigation options and that projects our findings into the future. While other integrated modeling endeavors have tested the implications of more extreme CCS scenarios, i.e. projecting climate policy costs in a world with and without CCS (Kriegler et al., 2013), we focus on the implications of a more ‘realistic’ set of CCS costs, as summarized by EP values. We simulate a broad set of scenarios that differ by: (i) short-term policy in relation to carbon pricing and public R&D for carbon capture; (ii) EP for carbon capture.

Our simulations indicate that there is some importance in modeling the future levels of EP with some precision, as different values impact the near term decisions on the size of CCS deployment as well as the type of power plant it is associated with. On the other hand, we note that by taking a portfolio approach, the worst case is not all that bad (since we consider the outcome of the best performing technology). The comparison between this worst case and the

outcome considering the most extreme pessimistic value provided by our experts highlights how it is important to consider a portfolio of CCS technologies and to devise policies flexible enough to allow for deployment of whichever technology turns out to be the best. While there are cost savings from a breakthrough, the overall lay of the land is not that different, suggesting that CCS policies can move forward without knowing exactly how successful it will be. Our results imply that the upside of an R&D investment dominates in most cases incentive-based technical change, and with even a small discount factor, R&D appears to be more efficient than a large near term carbon tax incentive.

Future work will extend the analysis of the results of the survey considering also questions related to investment costs and taking into account the ancillary information provided by the experts that can give further insights into the results.

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Appendix A

Possible choices of energy penalty metrics available to survey respondents:

<i>Type</i>	<i>Definition</i>
Change in power plant efficiency (%)	$EP_1 = 1 - \frac{\eta_{withCCS}}{\eta_{ref}}$
	$EP_2 = \eta_{ref} - \eta_{withCCS}$
	$EP_3 = \frac{\eta_{withCCS}}{\eta_{ref}}$

Change in input energy (%)	$EP_4 = \frac{\eta_{ref}}{\eta_{withCCS}} - 1$
Other	To be specified by the respondent

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