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Expert Elicitation of Cost, Performance, and RD&D Budgets for Coal Power with CCS

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Abstract

There is uncertainty about the ex-ante returns to research, development, and demonstration programs in the United States on carbon capture and sequestration (CCS) technology. To quantify this uncertainty, we conducted a written expert elicitation of thirteen experts in fossil power and CCS technologies from the government, academia, and the private sector. We asked experts to provide their recommended budget and allocation of RD&D funds by specific fossil power and CCS technology and type of RD&D activity (i.e. basic research, applied research, pilot plants, and demonstration plants) for the United States. The elicitation instrument was structured around estimating the cost and performance of coal-fired power plants with and without CCS in the years 2010 and 2030 under four funding scenarios for federal fossil energy RD&D in the USA. The most important areas identified for basic research were chemical looping combustion and membrane technology. The most important area for commercial demonstration was integrated gasification combined cycle (IGCC). There was substantial disagreement between experts on both the current and future capital cost to build a new coal-fired power plant with CCS. There was also disagreement across experts as to whether the capital cost of a new coal plant with CCS would increase or decrease if federal RD&D funding stayed constant at current levels. However, there was a consensus among our experts that accelerated federal RD&D would (weakly) lower the capital cost requirements for a new coal plant with CCS. On average, experts estimated that if their recommended RD&D portfolio was implemented, the capital cost of new coal plants with CCS in 2030 would decrease by 10% in addition to the cost reductions/increases that would occur by 2030 through non-public RD&D related factors.

Keywords: expert elicitation; research, development and demonstration; cost of CCS; modelling technical change

1. Introduction

In the energy sector, the goal of many research, development, and demonstration (RD&D) programs is to lower the cost of a delivered energy service by improving technology operating performance and/or reducing capital requirements. Ex-ante returns to RD&D investments are fundamentally uncertain, particularly for nascent

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technologies, yet despite this uncertainty, governments and the private sector continue to invest large sums to incentivize and conduct RD&D programs. For example, the 2009 stimulus package in the United States committed nearly $3.4 billion for carbon capture and sequestration (CCS) RD&D and the annual budget for CCS technologies, as requested by the President for fiscal year 2011 was over $400 million [1]. Around the world, policymakers seek to advance RD&D projects that span the breadth of RD&D activities, from basic research to large scale demonstration, for a wide range of CCS-relevant technologies. Over the past decade, as greater fractions of public accounts are directed towards RD&D projects, the effectiveness of the RD&D programs that are publicly supported is becoming of greater public relevance.

RD&D programs are distinct from other uses of public funds in that before funds are spent on an RD&D project, the results of interest (i.e. improved understanding and familiarity of technology construction or performance) are fundamentally uncertain. In order to make better informed decisions about how to set the level of RD&D funding and how to allocate funding across technologies and RD&D activities, a better understanding of the effectiveness of RD&D and its uncertainty is required.

2. Estimating Returns to RD&D

Determining the specific effectiveness of public RD&D is particularly difficult because of the uncertain extent of complementarity or substitutability between public research investment and private investment [2]. The empirical literature of historical case studies indicates that energy sector innovation increases when both *demand* for energy products increases and when the *supply* of energy technology-relevant knowledge increases [3]. However, even if government RD&D programs can affect either of these drivers of innovation (demand for energy technology or supply of relevant knowledge), the connection between government RD&D activity and actual technology cost and performance would still be unknown.

Theory and empirical studies on the effectiveness of RD&D improve understanding of what the effectiveness of RD&D might be on the future; however, extrapolation to actual future cases is often left unresolved. To our knowledge, there are three main classes of methodologies in the literature that have been use to quantitatively forecast future technology cost and performance metrics. The first class of methods decomposes long-term trends in technology cost [4,5]. The second class of methods uses monitoring for precursors [6]. The third is expert elicitation, a structured and systematic process for collecting and assessing probabilistic estimates from individuals with particular expertise of interest[2] [8,9].

In each of these approaches to technology forecasting, existing information is used to predict future metrics. However, to estimate RD&D effectiveness, an exogenous RD&D parameter should be included in the set of existing information that is leveraged to create predicted values. The extrapolation of cost reductions from historical data on the evolution of a technology excludes the possibility that technology may advance through new pathways and does not utilize the most recent knowledge in the field about possible breakthroughs. Expert elicitation allows for the quantification of uncertainty and can help decision makers collect information in cases where observable data is sparse or unreliable, and potentially useful data is unpublishable or proprietary.

Expert elicitation is different from surveys in that individual respondents are not treated as observations from a single population. Instead, expert elicitation treats individual respondents as representative of a large body of knowledge. Further, the emphasis of developing a “population” of experts to participate in an expert elicitation is on quality and diversity of expertise, not on quantity of participating experts [10]. The Delphi process, or expert consensus methods (such as those used by the reports of the Intergovernmental Panel on Climate Change), is a close sister methodology to expert elicitation. In a Delphi process, expert judgment is elicited in a group and the emphasis is to reach a consensus judgment [11]. In expert elicitation, each expert’s judgment is elicited individually. The advantage to expert elicitation is that each expert’s judgment is not influenced by other experts, avoiding unwanted group dynamic effects obscuring the true diversity of judgments [12]. The disadvantage of expert elicitation with respect to the Delphi method is that developing a coherent message from expert judgment is left up to the typically less-expert analyst.

[2] Expert elicitation has wide application beyond technology forecasting [7].

The results of our expert elicitation are predictions of technical change and can serve to support RD&D policy development as inputs to decision making tools. Decision makers increasingly rely on the results of computer energy-economy models [13,14]. Technical change within energy-economy models can be represented exogenously, endogenously, or as a combination of the two. Exogenous technical change is typically modeled with scenario analysis, using a range of assumptions of technical performance [15]. Endogenous technical change modeling typically utilizes technical "learning curves," relationships between the unit cost as a function of cumulative deployment [13]. Modelers who represent innovation endogenously typically parameterize learning curves of a technology of interest using historical data for the evolution of a similar technology. While modelers who represent innovation exogenously typically do not have sufficient information to choose scenarios that allow for policymakers to directly estimate the impact of RD&D policy.

3. The Expert Elicitation Instrument

In this paper we develop a unique elicitation instrument to quantify the uncertainty in returns (measured in technology cost reduction and performance improvement) for U.S. federal RD&D programs in fossil electric power including CCS technology. We administered the elicitation instrument to thirteen experts in fossil power and CCS technologies from the U.S. federal government, academia, and the private sector. Based on expert judgment, we quantify the stochastic effectiveness of RD&D programs in fossil power including CCS through 2030 in the USA. By eliciting cost and performance metrics for power plant technology under different RD&D funding scenarios, we can estimate the direct impact of RD&D on technology cost and performance holding all other factors constant.

We also collect expert judgment regarding the optimal allocation of RD&D funds across technology areas and RD&D activities (i.e. basic research, applied research, pilots, and commercial demonstration). The results of this study can be used to inform decision making to improve the allocation and level of RD&D funding in fossil power and CCS in the U.S. Department of Energy and in other countries. Further, these results may be particularly useful for parameterizing energy-economy models that are dependent on parameters not currently well measured in the body of published literature.

Eliciting the effectiveness of RD&D is challenging because of many possible conceptualizations for the "work" that RD&D does. We identified three quantifiable conceptualizations for the effectiveness of RD&D: 1) the increased (binary) likelihood of success in achieving a certain technical/cost metric (e.g. as used in [8]), 2) the acceleration in the number of years required to reach a certain technical/cost metric, 3) the adjusted range of expected cost and efficiency of providing a certain service at a specified time. In this work, we have used the latter (third) conceptualization, hypothesizing that the experts we consulted more frequently think about the range of possible cost and performance outcomes of research in a field, rather than the probability of achieving an a priori set goal (defined by the researcher) or the number of years until a technological milestone will be reached. We also hypothesize that given uncertainty, when the slope of cost or performance metrics over time is relatively flat, there is greater uncertainty in the time dimension than in the cost or performance dimension. Therefore, eliciting actual cost and performance metrics may provide a more reliable method for eliciting an expert's true understanding of each uncertain dimension.

The elicitation instrument we developed sought to provide a common base level of minimum information to prime experts equivalently in common tendencies in uncertainty estimation and elicit estimates and recommendations in a consistent and controlled manner. The instrument included a background information section that detailed recent federal RD&D budget activity in fossil power, including the 2009 American Recovery and Reinvestment Act (ARRA). This section also provided adjusted cost and performance metrics based on Al-Juaied and Whitmore [16] for coal-fired and natural gas-fired power plants with and without CCS. These estimates were drawn from the available literature for the levelized cost of electricity, total plant capital cost, and plant efficiency. Experts were also provided with baseline financing assumptions drawn from MIT [17] and fossil fuel price projections drawn from EIA [13]. To familiarize experts with providing uncertainty estimates, the elicitation instrument included primers on reducing bias and overconfidence and estimating percentiles of a distribution. Experts were also asked to assess their level of expertise on specific fossil and CCS technologies.

The next section of the elicitation instrument asked experts to estimate cost and performance metrics for new coal-fired power plants in 2010 and in 2030, each with and without CCS, assuming federal RD&D spending does not change from current levels and no price on greenhouse gas emissions is established. For all types of power plants, experts evaluated the best available 500 MW power plant compliant with current Clean Air Act regulations (i.e. new source performance standards). For each type of power plant, experts provided 10th, 50th, and 90th percentile estimates for the overnight capital cost, and 50th percentile estimates for the plant's generating efficiency, capacity factor, and book life. Our choice of questions and parameters was shaped by the existing structure of the energy-economic modeling tool we are using for subsequent analysis, the U.S. ten-region MARKet ALlocation (MARKAL) model developed by Brookhaven National Laboratory [14]. For the remainder of this paper, 2010 estimates are referred to as "reference estimates" and 2030 estimates assuming federal RD&D does not change from current levels are referred to as "business-as-usual estimates" or "BAU estimates."

After providing reference and BAU estimates, experts were asked to provide their recommended level and allocation of federal RD&D spending. Each expert was provided with a "game board" that divided fossil power technologies into sixteen technology areas (and an optional seventeenth area to be specified by each expert). Experts were asked to allocate 100 poker chips, each representing 1% of their total recommended RD&D portfolio to the sixteen technology areas. Within each technology area, experts were asked to further allocate across four classes of RD&D activity: basic research, applied research, experiments/pilots, and commercial demonstration. Upon completion of the game board, several qualitative budget discussion questions were asked.

In the next section of the elicitation instrument, experts revised their BAU estimates with respect to three scenarios of future RD&D funding and allocation: the budget and allocation they recommended, only half of their recommended budget (allocated proportionally to their original recommendation), and ten times their recommended budget (also allocated proportionally). Overall, the scenarios were designed to allow an analysis of the experts' view on what federal RD&D investments could "buy" while ascertaining the sensitivity of results to a range of spending levels. The scenario of ten times each expert's recommended budget was chosen to test the limit of what federal RD&D could achieve. The final section of the elicitation instrument asked experts to estimate other risk factors that may affect the deployment of CCS.

Experts were chosen after a review of the peer-reviewed literature, conferences, and reports on fossil energy and CCS in the USA. Invitations to participate in the survey were sent to ninety experts in February 2010, and thirteen experts, shown in Table 1, returned at least partially completed elicitation instruments by July 2010 via mail.

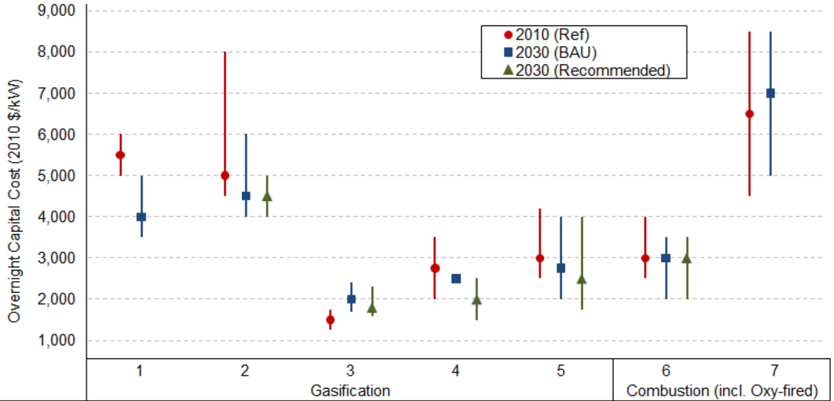
Table 1. Participating experts and their institutions

Name	Institution	Name	Institution
Gary Stiegel	National Energy Technology Laboratory	Doug Cortez	Hensley Energy Consulting, LLC
Janos Beer	Massachusetts Institute of Technology	Manoj Guha	Energy & Environmental Services Int'l
James Dooley	Pacific Northwest National Laboratory	Gary Rochelle	University of Texas, Austin
Stephen Moorman	Babcock & Wilcox	Jay Braitsch	U.S. Department of Energy
Jost Wendt	University of Utah	Joseph Smith	Idaho National Laboratory
Reginald Mitchell	Stanford University	Jeffrey Eppink	Enegis, LLC
Joe Chaisson	Clean Air Task Force		

4. Results

4.1 Elicitation Results and Simulated Capital Cost Distributions

Seven experts provided overnight capital cost estimates of a new coal-fired power plant with CCS for at least the reference and BAU scenarios, and five experts also provided estimates for the 2030 scenario in which their recommended RD&D portfolio was implemented. Figure 1 displays the capital cost estimates of the experts, revealing large disagreement, even in the 2010 reference scenario. The Figure also displays the median estimate for the plant efficiency in the 2030 BAU scenario. Across scenarios, experts estimated that the plant efficiency for a coal plant with CCS would not change substantially as a result of RD&D.



	1	2	3	4	5	6	7
2030 BAU Eff. (HHV %)	40	35	35	40	36	35	33
endogenous reduction (%)	27	10	-33	9	8	0	-8
exogenous reduction (%)	N/A	0	10	20	9	0	N/A

Figure 1. Cost and performance estimates for a new coal-fired power plant.

By using their capital cost probability distributions in a Monte Carlo analysis, weighing each expert equally, we are able to approximate the collective insight that we seek. In order to do this, we calculated distribution functions for each expert's estimates of capital cost. The simulated cumulative distribution function with 100,000 simulations is shown in Figure 2 for the estimated capital cost in four scenarios (reference 2010, BAU 2030, and two 2030 RD&D funding scenarios). The Monte Carlo analysis was done to concisely summarize results for understanding the range of results we obtained. The Figure shown does not account for differences in the expert's opinion on current costs, their familiarity estimating percentiles, and is therefore not used in the remainder of the paper beyond this section. The simulated distributions indicate that experts believe that it is very likely that for a new coal plant with CCS, the 2030 BAU capital cost will be lower than technology that could currently be deployed, absent any additional policies. At median values, the simulated 2030 capital cost under the recommended RD&D portfolios is $2,400/kW whereas the 2030 capital cost under the BAU portfolio is $3,600/kW, for a median cost reduction of $1,200/kW. This captures both the cost reductions attributable to technical change that will occur over time absent RD&D policy and the cost reductions that will be driven by federal RD&D policy. The simulated distribution under the recommended and ten times recommended RD&D scenarios highlight the experts' perception about the role of RD&D policy driving innovation in the area. Given that absent a price on carbon, CCS will not have a market, it is not surprising that greater cost reductions are estimated for these scenarios. At the 50th percentile of the Monte Carlo distribution, the recommended RD&D scenario reduces the capital cost from 2030 levels by $1,220/kW and the 10-times scenario reduces the capital cost from 2030 levels by $1,660/kW.

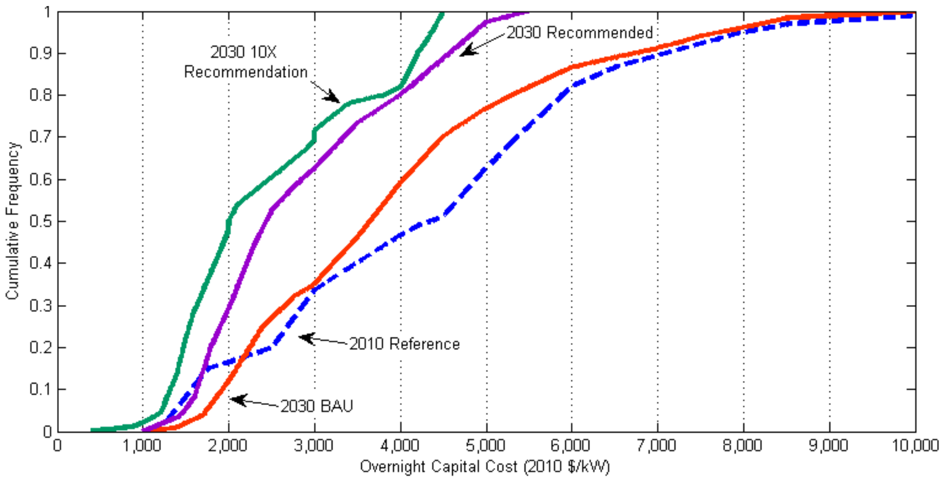


Figure 2. Capital cost of a new coal power plant with CCS - simulated results from expert judgment

The capital costs reported in the literature for a new Nth of a kind (NOAK) CCS plant can be adjusted for consistent and updated raw material costs, financing parameters, and operating conditions, allowing comparisons [16]. Adjusted point estimates from the literature for all types of coal-fired CCS technology (post-combustion, pre-combustion, and oxy-fired combustion) span $2387/kW to $4168/kW[3]. The range of adjusted estimates from the literature falls between the 24th and 63rd percentiles on the 2030 BAU distribution, whereas the literature range falls between the 48th and 83rd percentiles on the 2030 distribution of capital costs assuming each expert's recommended level of RD&D is implemented. This suggests that the literature better captures what the experts described would be likely when RD&D funding does not change, while placing likely costs on the upper end of the distribution when RD&D funding is expanded.

4.2 Exogenous and endogenous rates of technical learning

The design of our elicitation allows us to differentiate between *exogenous* and *endogenous* technical learning. Experts provided estimates of the current (2010) capital cost of a new build coal plant with CCS and the capital cost in 2030 assuming four possible RD&D scenarios. For each expert, we estimate the endogenous rate of technical change from 2010 to 2030 as the ratio of the median BAU 2030 capital cost of a new coal plant with CCS to the estimated median reference capital cost of a new coal plant with CCS in 2010. This is *endogenous* in the sense that the cost reductions cannot directly be affected as they are due to changes in the macro-economy, spillovers from other technology areas, and learning by doing. The effectiveness of RD&D through accelerated federal RD&D is captured by the exogenous rate of technical change. We estimate this as the ratio of the median 2030 capital cost of a new CCS plant under an advanced RD&D portfolio to the estimated median 2030 capital cost of a new CCS plant in the BAU scenario. This is *exogenous* in the sense that the factor driving this change is known and the inputs can be set by decision makers.

Although there is large disagreement on overall rate of technical change, there is greater consensus on the rate of exogenous technical change than on the rate of endogenous technical change. Four experts thought that under BAU funding the capital cost of a new coal plant with CCS would not become less expensive (in real terms) by 2030. The most optimistic expert estimated that capital costs would decrease 27% from 2010 to 2030 under the BAU scenario, while the most pessimistic expert estimated that capital costs would increase 33%.

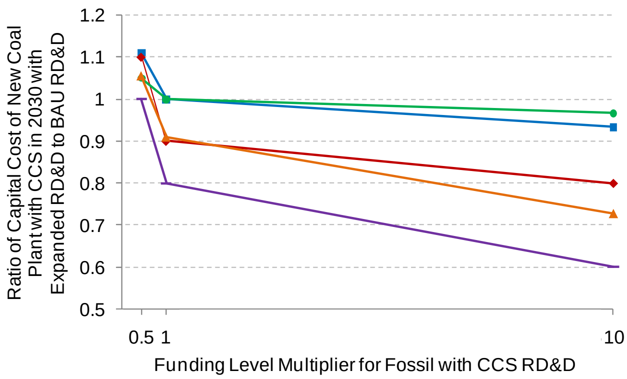


Figure 3. Overnight capital cost reduction from BAU scenario at 3 levels of RD&D funding

The exogenous technical change can be calculated for three scenarios of accelerated RD&D funding. The smaller rate of exogenous technical change is calculated as the ratio of the estimated 2030 capital of a new CCS plant under each expert's recommended RD&D portfolio to the same expert's estimated 2030 capital cost given BAU RD&D funding. The larger rate of exogenous technical change is calculated similarly, instead using each expert's estimate under the scenario that RD&D funding is set at 10 times the recommended level as the numerator. Whereas the spread across experts in median estimated endogenous technical change is 61 percentage points, the spread across experts in median estimated exogenous rate of technical change is 20 percentage points for the smaller rate and 37 percentage points for the larger. The most optimistic expert estimated the small rate of exogenous technical change

[3] The ranges do not represent uncertainty in the typical sense, but rather the full range of estimates in the reviewed studies.

at 20% and the larger rate at 40%. The most pessimistic expert estimated the smaller rate of exogenous technical change at 0% (i.e. the expert's recommended RD&D portfolio would have no effect on the median capital cost of a new CCS plant beyond what would occur given BAU RD&D). The most pessimistic expert estimated the median large rate of technical change at 3%. Figure 3 shows the median values of cost reductions from the 2030 BAU scenario as a function of RD&D investments, highlighting the expected decreasing marginal returns to RD&D.

4.3. Allocation of RD&D Funding

All thirteen experts provided input on the optimal allocation of RD&D funds using the budget "game board." The average recommendation for the optimal level of RD&D funding for fossil energy and CCS was $2.3 billion/year, well above the current $400 million/year in RD&D funding allocated to fossil power and CCS [1]. Experts placed strong emphasis on commercial demonstration, on average recommending that over 40% of the total RD&D budget for fossil energy be allocated for this purpose (the maximum and minimum fractions experts dedicated for demonstrations are 80% and 15%, respectively). Within commercial demonstration, experts emphasized commercial demonstrations of IGCC, oxy-fired combustion and retrofitting existing plants for CCS. Experts allocated over 30% of their budgets for these purposes, on average emphasizing chemical looping combustion and membrane technology.

Across all types of research, IGCC was seen as the most important technology area to invest RD&D funds in. However, when the enabling technologies for post-combustion/oxy-fired combustion capture (chemical absorption, physical absorption, adsorption, membranes, oxy-fired combustion, and retrofitting existing plants) are aggregated, experts recommend allocating over three times more funding for post-combustion/oxy-fired combustion than for IGCC. In the FY 2011 budget request, this relationship was reversed, with over 2.2 times more funding for IGCC than for post-combustion/oxy-fired combustion capture (including retrofitting). In the ARRA, the federal government invested over $2 billion for fossil and CCS RD&D. Of the $2 billion, over 75% was allocated for IGCC. [18]. Figure 4 shows the average annual allocation in million U.S.$ across expert recommendations for each fossil and CCS technology area by type of research activity.

	Capture Technologies				Power from Coal					Natural Gas	Fuels	Crosscutting Research Areas					Other
	Chemical absorption	Physical absorption	Adsorption	Membranes	Pulverized/fluidized bed coal combustion	IGCC	Oxy-fired combustion	Underground coal gasification	Chemical looping combustion	Advanced turbines	Resource assessment	Non-power products (co-production)	Fuel Cells	Retrofitting existing plants for CCS	Sensors and controls	Non-Co2 environmental control	e.g. materials, novel capture methods
Basic Research	12	16	18	33	14	22	20	21	27	7	6	9	16	12	7	9	21
Applied Research	22	19	25	28	27	36	41	38	50	25	18	19	46	25	15	8	24
Experiments and Pilots	29	26	21	30	23	73	67	31	50	36	17	24	34	59	9	17	33
Commercial Demonstration	70	30	21	35	26	221	167	32	29	76	18	64	44	145	9	15	42
Total	133	90	85	126	90	352	295	122	155	144	59	116	140	240	39	49	120

Figure 4. Average recommended RD&D funding for fossil power and CCS technologies in 2010$ mil.

We tested for the possibility that expert budget recommendations were correlated with self-reported expertise in technology areas. The budget recommendations that our experts reported were only weekly correlated with self-reported expertise, and in some cases the correlation was negative. The two technology areas with the greatest correlation between expertise and recommended RD&D funding level were oxy-fired combustion and membrane technology where the correlation between expertise and budget recommendation were 0.44 and 0.48, respectively. Whether or not this is a case for concern is ambiguous as this correlation could arise because experts sought to make self-serving recommendations in the hopes of receiving a portion of the RD&D funds they recommended or experts developed expertise in a technology area after learning that the technology was an important area for RD&D.

5. Conclusion

We conducted an expert elicitation of CCS technology applied to coal-fired power plants that estimated the effectiveness of federal RD&D in the USA. Reflecting CCS technology's early stage of maturity, our elicitation revealed large disagreement between experts on the capital cost a new coal plant with CCS, consistent with the findings of Baker, et al. [19]. There was significant disagreement in both present and future estimates of the cost to build a new CCS plant. This disagreement may have been heightened by differences in each expert's access to information, familiarity estimating percentiles, and degree of confidence in their own predictive capability. However, by normalizing cost estimates by a reference scenario, we found that there was greater consensus on the role of RD&D on catalyzing cost reductions in CCS technology. At best, the experts expect that the RD&D portfolios they recommended alone can reduce the median capital cost of a new coal plant with CCS in 2030 by 20% and at worst, RD&D policy does not affect the central tendency of the cost of CCS.

To realize these cost reductions, experts recommend an average increase in federal RD&D funding in the USA to $2.3 billion/year through 2030. No expert recommended maintaining or reducing RD&D funding from current levels (approximately $400 million/year). Participating experts recommended allocating RD&D funds heavily weighted to commercial demonstration, with an emphasis on IGCC, retrofitting existing plants for CCS, chemical absorption, and oxy-fired combustion. On average, experts would allocate over 40% of their recommended RD&D to commercial demonstration and 25% to experiments and pilots.

The expert elicitation methodology presented in this paper allows for exogenous and endogenous technical change to be estimated while still allowing experts to provide estimates in metrics they are familiar with. Furthermore, this elicitation allowed us to control for differences in each expert's cost baseline, which gave a more consistent estimate of the range of the impact that may be expected as a result of RD&D policy. These results are particularly useful for energy-economic models that currently lack a data-driven justification for representing technical change and its uncertain nature. The combination of the type of expert elicitation presented in this paper with energy-economic models could help RD&D policy makers by allowing them to incorporate the uncertainties associated with technical change into the decision-making process.

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References

[1] U.S. Department of Energy, Office of the CFO. Department of Energy FY 2011 congressional budget request (DOE/CF-0049); 2010.
[2] David P, Hall B, Toole A. Is Public R&D a complement or substitute for private R&D? A review of the econometric evidence. Research Policy 2000; 29:497-529.
[3] Popp D. Induced innovation and energy prices. American Economic Review 2002; 92:160-80.
[4] Nemet G. Beyond the learning curve: factors influencing cost reductions in photovoltaics. Energy Policy 2006; 34:3218-32.
[5] McNerney J, Trancik J, Farmer JD. Historical costs of coal-fired electricity and implications for the future. Santa Fe Institute Working Paper Series 2010; #09-12-047.
[6] Martino J. Using precursors as leading indicators of technological change. Technological Forecasting and Social Change 1987; 32:341-60.
[7] Morgan MG, Keith D. Subjective judgments by climate experts. Environmental Science & Technology 1995; 29:468A-76A.
[8] Baker E, Chon H, Keisler J. Advanced solar R&D: combining economic analysis with expert elicitations to inform climate policy. Energy Economics 2009; 31:S37-49
[9] Curtright A, Morgan MG, Keith D. Expert assessment of future photovoltaic technology. Env. science & technology 2008; 42:9031-8.
[10] Cooke, R. Experts in uncertainty: opinion and subjective probability in science. New York: Oxford University Press; 1991.
[11] Dalkey N. The Delphi method: an experimental study of group opinion. RAND Report 1969; #RM-5888-PR.
[12] Oppenheimer M, O'Neill B, Webster M, Agrawala S. The limits of consensus. Science; 317:1505-6.
[13] U.S. Energy Information Administration. Assumptions to the annual energy outlook 2010 (DOE/EIA-0554(2010)); 2010.
[14] Fishbone L, Abilock H. Markal, a linear-programming model for energy systems analysis. Int'l journal of energy research 1981; 4:353-75.
[15] Kyle P, Clarke L, Pugh G, Wise M, Calvin K, Edmonds J, Kim S. The value of advanced technology in meeting 2050 greenhouse gas emission targets in the United States. Energy Economics 2009; 31:S254-67.
[16] Al-Juaied M, Whitmore A. Realistic costs of carbon capture. Belfer Center for Science and Int'l Affairs discussion paper 2009; #2009-08.
[17] MIT. The future of coal; 2007.
[18] Anadon LD, Bunn M, Chan G, Chan M, Gallagher KS, Jones C, et al. DOE FY 2011 budget request for energy research, development, demonstration, and deployment: analysis and recommendations. Report for Belfer Center for Science and International Affairs 2010.
[19] Baker E, Chon H, Keisler J. Carbon capture and storage: combining economic analysis with expert elicitations to inform climate policy. Climatic Change 2009; 96:379-408.