Understanding Barriers to Commercial-Scale Carbon Capture and Sequestration in the United States: An Empirical Assessment

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Abstract

Although a potentially useful climate change mitigation tool, carbon capture and sequestration (CCS) efforts in the United States remain mired in demonstration and development. Prior studies suggest numerous reasons for this stagnation. This article empirically assesses those claims. Using an anonymous opinion survey completed by 229 CCS experts, we identified four primary barriers to CCS commercialization: (1) cost and cost recovery, (2) lack of a price signal or financial incentive, (3) long-term liability risks, and (4) lack of a comprehensive regulatory regime. These results give empirical weight to previous studies suggesting that CCS cost (and cost recovery) and liability risks are primary barriers to the technology. However, the need for comprehensive rather than piecemeal CCS regulation represents an emerging concern not previously singled out in the literature. Our results clearly show that the CCS community sees fragmented regulation as one of the most significant barriers to CCS deployment. Specifically, industry is united in its preference for a federal regulatory floor that is subject to

state-level administration and sensitive to local conditions. Likewise, CCS experts share broad confidence in the technology's readiness, despite continued calls for commercial-scale demonstration projects before CCS is widely deployed.

Keywords: Carbon capture and sequestration, Climate change mitigation, Climate policy

1. Introduction

Coal consumption rests at the intersection of energy policy's threefold objectives: providing (1) ample, secure supplies that are (2) low cost and (3) environmentally sustainable (Lyster and Bradbrook, 2006). Coal is abundantly used in the United States, providing nearly half of the nation's electricity production (EIA, 2012), but it is also linked to climate change. Worldwide anthropogenic carbon dioxide (CO_2) emissions currently total more than 33 billion tons annually (PBL, 2011), a level now recognized as unsustainable (IPCC, 2007). Concerns over climate change and national energy security have prompted a reexamination of fossil fuel use, including coal.

Carbon capture and sequestration (CCS) is one possible strategy for tapping the energy security benefits of coal while simultaneously mitigating climate change emissions. CCS is the process of capturing CO_2 and injecting that CO_2 deep underground for permanent storage and sequestration.[1] CCS can be used with other fossil fuel combustion processes, such as natural gas, but it is most closely linked with coal-fired electricity generation.

Despite extensive governmental backing, CCS development has proceeded in halting starts and stops in the United States. According to the Global CCS Institute, as of September 2012, the United States had twenty-four large-scale CCS projects in the planning or operational stages. Only four of these projects, however, were operational, and these were connected to

enhanced oil recovery efforts. Moreover, these twenty-four projects represent a decreasing effort in large-scale CCS efforts, down from thirty-one large-scale CCS projects underway in 2010 (Global CCS Institute, 2012).

Prior studies have suggested numerous reasons for this stagnation, but these explanations have been subjected to limited empirical testing. This article seeks to advance the discussion by presenting empirical data on both CCS impediments and potential policy responses to CCS commercialization barriers. To do so, we conducted an anonymous opinion survey of 229 stakeholders in CCS technology development, CO_2 emitting industries, CCS regulation, and other areas of CCS expertise. The survey had five goals: (1) to identify perceived barriers to commercial-scale CCS deployment, (2) to rate the significance of those barriers, (3) to compare the severity of perceived barriers across sectors, (4) to identify discrepancies between perceived barriers and CCS policies, and (5) to provide a basis for future CCS policy recommendations.

The survey data provide new insight into how CCS policy might be shaped. They also confirm prior studies' emphasis on cost and liability concerns as primary barriers to CCS implementation. Thus, to help CCS reach widespread commercial use, a carbon price or other significant financial incentive is needed, and the liability risks of long-term CO_2 storage must be addressed. Moreover, the CCS community craves a predictable, comprehensive regulatory regime—something overlooked by the extant scholarly literature, which has tended to focus on discrete legal and regulatory issues. The survey data suggest that this regime should employ a dynamic, or cooperative, federalist model of regulation—that is, one where national regulators set minimum legal requirements but state officials craft the specific implementation measures for those rules to account for local conditions. This regime would likely include eventual federal ownership of stored CO_2 and control over interstate CO_2 transport, pipelines, and all aspects of

offshore CCS, but would not disturb traditional areas of state control (*e.g.*, property rights, pore space ownership, mineral rights unitization, and eminent domain). It also would not place first priority on commercial-scale demonstration projects, and would instead emphasize tax credits and incentives over other options, such as technological mandates, subsidies, and funding for research and development.

2. Possible Barriers to CCS Commercialization

Although prior CCS studies are numerous, the scholarly literature has not yet systematically assessed the barriers to commercial-scale CCS deployment in the United States. Instead, scholarly empirical studies have focused primarily on Europe (Anderson et al., 2007; Evar, 2011; Fischebick et al., 2009; Hansson and Bryngelsson, 2009; ICF, 2007; Johnsson et al., 2010; Ramírez et al., 2008; Sala and Oltra, 2011; Stigson et al., 2012; van Alpen et al., 2007; Wallquist et al., 2010). Within the United States, CCS studies tend to focus on qualitatively outlining impediments that CCS commercialization faces, without any empirical evaluation. Other authors have highlighted government incentives, concentrating on options for promoting CCS (DeCesar, 2010; Flatt, 2009; Som 2008). Still others have zeroed in on public perception of CCS and climate change (Bradbury et al., 2009; Curry, 2004). While often recognizing that regulatory uncertainty acts as an impediment to CCS commercialization, most of the law and policy literature has emphasized specific legal issues, such as potential CCS liability mitigation regimes, pore space ownership, or CO_2 pipeline regulation.

Potential barriers to CCS commercialization identified in prior studies include cost, the need for commercial-scale demonstration projects, liability and property rights issues associated with long-term CCS storage, safety and siting concerns, and the need for greater geologic knowledge and predictive modeling capabilities (Carnegie Mellon, 2009; Folger, 2009; GAO,

2008; IEA, 2007; IEA, 2010; IPCC, 2005a; IRGC, 2008; Melzer, 2008; NETL, 2006; Parker et al., 2009; Pew Center, 2008; University of Houston, 2008; WRI, 2007; WRI, 2008). Scholars have also noted the general public's limited knowledge about CCS and the technologies involved (Bradbury et al., 2009; Curry, 2004), while others have suggested that public outreach is necessary to build trust between communities and project developers, and to counteract what has been characterized as a "pessimistic" public attitude about CCS (Carnegie Mellon, 2009; DOE, 2010; WRI, 2008).

Of these various barriers, the higher cost of CCS-based electricity production, associated largely with the energy penalty from the CO_2 capture phase of CCS, has received the greatest attention (Der, 2010; GAO, 2008; Melzer, 2008; Pew Center, 2008). Estimates place the cost of retrofitting an existing power plant with CCS technology, as reflected by the increased cost of electricity, at 50-80% above existing costs (Carbon Capture and Storage Technologies Hearing, 2008; FutureGen Program Hearing, 2008). The absence of any financial incentive for CCS, such as a carbon price, is thus viewed as a fundamental barrier to CCS deployment (DOE, 2010; GAO, 2008; Pew Center, 2008). This relationship may create a Catch-22 of sorts. As Folger observes, "To achieve commercialization, [CCS] must . . . meet a market demand—a demand created either through a price mechanism or a regulatory requirement (demand-pull mechanisms)" (Folger, 2009). The failure of the United States to create a market reflecting the true price of carbon therefore serves as a disincentive for CCS deployment (Der, 2010; Pew Center, 2008), leading some commentators to suggest that CCS is unlikely to be economically favorable in the United States for at least two decades (JP Morgan, 2007). Focusing on price, the literature also advocates for research and development to increase CCS cost-effectiveness (GAO, 2008), along

with addressing the capital costs that the extensive pipeline infrastructure that broadscale CCS would entail (DOE, 2010; WRI, 2008).

After cost, liability receives the greatest attention as an impediment to CCS deployment (Attanasio, 2009; Bidlack, 2010; DOE, 2010; Hoffman, 2010; Klass and Wilson, 2008; Som, 2008). Liability for CO_2 storage is unclear. Two groups potentially bear the primary long-term legal risks for post-injection CO_2 management: private companies that take on CCS projects and the government/taxpayers. Which group ultimately will bear the risk is an open question (Carbon Capture and Storage Technologies Hearing, 2008). Accordingly, numerous observers have highlighted the uncertainty surrounding potential liability for carbon storage as a key source of industry reluctance for CCS investment (Carbon Capture and Storage Technologies Hearing, 2008; Carnegie Mellon, 2009; Chestney, 2009; DOE, 2010). To address this barrier, observers have proposed a number of possible liability strategies, including traditional bonding and insurance, statutory liability limits, imposing responsibility on states, mandating federal ownership for stored CO_2, and various hybrid private-public solutions (Carnegie Mellon, 2009; DOE, 2010; Flatt, 2009; WRI, 2008).

Policy studies have also observed CCS's need for continuous monitoring, especially via risk assessment and mitigation measures following CO_2 injection (DOE, 2011; NETL, 2009). While monitoring strategies must be site-specific to account for local surface and subsurface variations, these studies suggest that a comprehensive regulatory framework for monitoring, mitigation, verification, and accounting will be essential for wide-scale CCS deployment (DOE, 2011; NETL, 2009). This is in part because of CCS's potential for groundwater contamination and displacement (Folger, 2009; IRGC, 2008), but also because CCS presents many unanswered property law questions (Anderson, 2009; DeCesar, 2010; Fish and Wood, 2008; Flatt, 2009;

Kennett et al., 2006; Klass and Wilson, 2010; Sprankling, 2008; University of Houston, 2008). Many of these questions are matters of state rather than federal law, and as such, could be resolved in multiple and potentially conflicting ways.

Discussions of general CCS regulation follow a similar refrain. Throughout the CCS literature, "[r]egulatory uncertainty is widely identified as a key barrier to CCS deployment in the United States" (DOE, 2010). However, while some studies have questioned whether a comprehensive CCS framework is needed (University of Houston, 2008), most focus on how existing statutory regimes will apply to CCS (DOE, 2010; GAO, 2008; Marston and Moore, 2008). The chief concern from a CCS deployment perspective is the need "to ensure that [the] effective operation [of these laws] does not hamper CCS for no additional benefit" (University of Houston, 2008; Moore, 2007). This is because numerous existing statutes already are, or may soon, impact CCS development. In addition to emerging state regulatory regimes (Reitze and Durrant, 2011), these include the Safe Drinking Water Act, the Clean Air Act, the Resource Conservation and Recovery Act, the National Environmental Policy Act, the Endangered Species Act, and Department of Transportation pipeline regulation (DOE, 2010; Horne, 2010; Marston and Moore, 2008; Reitze, 2011).

A final impediment to broadscale CCS deployment cited widely in the literature is the lack of sufficient commercial-scale demonstration projects (GAO, 2008). Although CO_2 is currently utilized in several industrial applications, technological advancements will be required before existing CCS technologies are widely deployed (Der, 2010; DOE, 2010). These include scale-up challenges for capture technologies at power plants, the need for a nearly pure CO_2 stream for CCS transport and storage, and the ability to verify the permanence of CO_2 storage underground (DOE, 2010; GAO, 2008). Accordingly, many studies question the appropriate

level of federal investment in CCS R&D (Der, 2010; Parker et al., 2009), with some noting that current DOE spending on CCS is far below past government efforts at major technological innovation such as the Manhattan Project and the Apollo program (Parker et al., 2009). In addition to carbon pricing, the literature suggests four primary approaches for funding CCS: (1) government loan or grant programs; (2) direct government financial incentives, such as tax credits; (3) private industry funding; and (4) international collaboration (Carbon Capture and Storage Technologies Hearing, 2008; Der, 2010; IRGC, 2008).

3. Survey Methodology

Consistent with prior studies seeking to ascertain how policy might best promote emergent technologies (Bowen, 2012; Bürer and Wüstenhagen, 2009; Hansson and Bryngelsson, 2009; Johnsson, 2010; Evar, 2011; Sala and Oltra, 2011; Stigson et al., 2012), our survey targeted experts in CCS technology, policy, and implementation. Our study focused on CCS deployment and policy in the United States, so unlike some earlier surveys, only companies and organizations with a domestic presence were included. Potential survey recipients were identified based on participation in established CCS industry and research and development programs, including U.S. Department of Energy (DOE) regional carbon sequestration partnerships, attendance at CCS conferences and seminars, and participation in other CCS projects.

Survey questions were developed based on issues identified through a review of CCS literature and policy. Surveys were pretested on University of Utah faculty and staff during the fall of 2011; the survey was administered during early 2012. Each recipient received a unique, password-protected internet link to access and complete the survey. All responses were anonymous, and participants received no compensation for participating.[2]

Survey participation was robust. In total, 229 out of 501 survey recipients responded to the survey (45.7%). Of those, 195 recipients, or 85.2%, completed the survey in its entirety. Survey respondents fell into six possible affiliations: CCS operators, CCS researchers, CO_2 emitters, CCS consultants (including legal, financial, and engineering), government agency employees or regulators, and interest group representatives.

Consistent with standard survey methodology (Hauser and Rao, 2002; Wind et al., 1979), the survey included both open-ended questions and numerical ranking questions. To avoid suggestion bias, open-ended questions preceded ranking questions (Hauser and Rao, 2002; Wind et al., 1979). Participants also provided generic affiliation data, including their role in CCS. These categories of questions are referred to as the survey's "open-ended," "ranking," and "demographic" questions respectively. Figure 1 details survey respondents demographically.

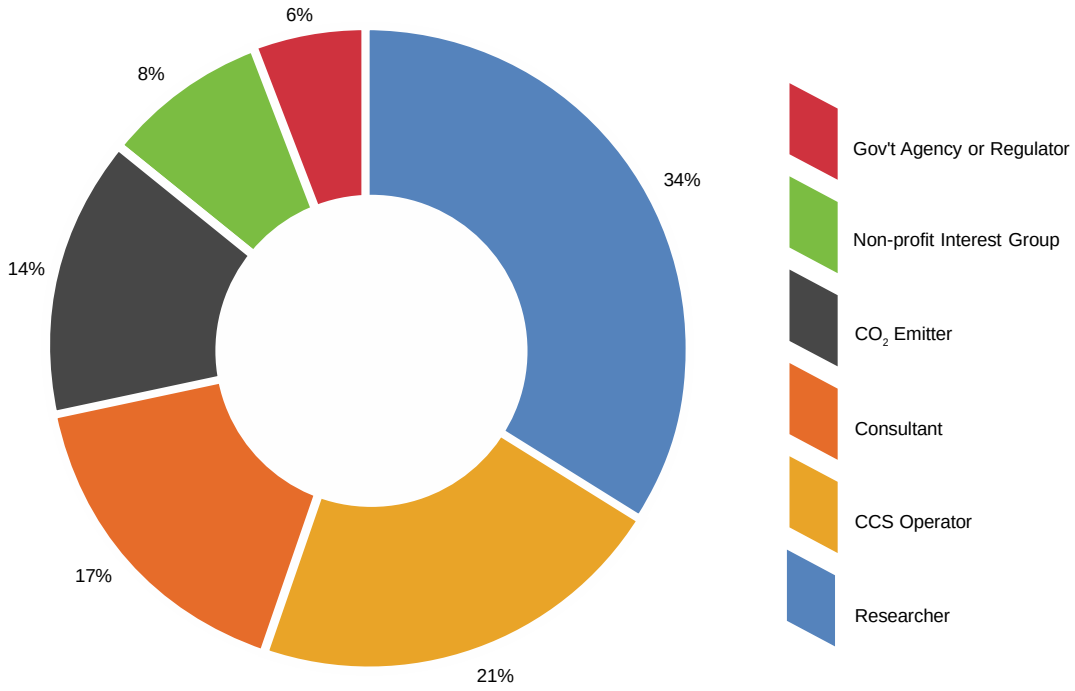


Figure 1: Number of Respondents by Affiliation

The ranking and open-ended questions cut across three primary areas of inquiry: potential barriers to CCS commercialization, possible government efforts to promote CCS, and potential CCS policy. In the ranking questions, respondents ranked forty-one possible barriers to CCS commercialization on a one-to-five scale. Possible barriers to CCS commercialization were identified based on a literature and policy review. *See supra* Section 2. These forty-one potential barriers fell into seven broad categories: CCS cost, liability, facility siting, technology insufficiency, lack of a CCS price signal, lack of a CCS regulatory regime, and public resistance to CCS.[3] For each broad category, the survey included one catchall question and then more specific questions about discrete elements of the barrier class. Respondents also ranked their level of agreement with seventeen different statements about CCS regulation. A chart showing responses to all questions, including mean scores and standard deviations, is available at http://dx.doi.org/10.1016/j.enpol.2013.04.033. In the figures that follow, shading represents the range of responses that fall within one standard deviation of the mean response value. Values shown in bold and italics were statistically significant at the .05 level when measured against overall mean scores.

Textual responses to the open-ended questions were analyzed and placed into categories corresponding to the ranking questions. To avoid coding bias, two researchers coded the open-ended responses independently and compared results only after coding was complete. Where coding differences occurred, they were reconciled through collaborative review of the textual answers.

4. Results

The survey results provide three key contributions to understanding CCS commercialization in the United States. First, the survey data offer empirical confirmation of

what, previously, have been generally anecdotal and qualitative suggestions about the barriers faced by broadscale CCS in the United States. The survey results show that there are four primary, interrelated barriers to CCS commercialization: cost and cost recovery, lack of a price signal or financial incentive for CCS use, liability, and lack of comprehensive CCS regulation. CCS cost, no price signal for CCS use (*e.g.*, lack of climate change legislation), and liability risks all have repeatedly been pointed to as impediments to CCS commercialization. Our data empirically confirm this traditional logic. Indeed, cost and cost-recovery are perceived by the CCS community to be the greatest obstacles to CCS deployment.

Second, the survey findings call into question several conventional assumptions that have been made about CCS. For instance, survey respondents identified the lack of a comprehensive CCS regulatory regime as a primary obstacle to CCS deployment. However, this is not a barrier to CCS use that previously has received substantial scholarly attention. Likewise, many prior studies have suggested that a key impediment to CCS deployment is the lack of commercial-scale demonstration projects (GAO, 2008). By contrast, several survey respondents expressed relative confidence in CCS technology compared to other CCS barriers. Indeed, respondents' experience with, and confidence in, CCS technology were positively correlated.

Finally, the survey results provide significant new detail on the type of policy and regulatory regime that the CCS community desires. Market incentives are favored over statutory mandates. These preferred incentives include tax/financial incentives, liability limits, a comprehensive CCS regulatory framework, and a carbon tax. Similarly, the CCS community wants clear, comprehensive regulation, including liability limits and a cooperative federalist approach to regulation. The preferred form of liability protection includes the government taking long-term responsibility for sequestered CO_2.

These findings fall into the three broad classes of questions answered by survey respondents: barriers to CCS commercialization, preferences on financial incentives, and regulatory substance and structure.

4.1. Barriers to CCS Commercialization

The survey results identified four primary, interrelated barriers to commercial-scale CCS deployment: (1) the high marginal cost of incorporating CCS into electricity production and the inability to recover CCS costs, (2) the lack of a price signal to incentivize CCS use, (3) long-term liability for sequestered CO_2, and (4) the lack of comprehensive CCS regulation.

By contrast, a number of possible barriers previously identified in the literature received lower mean scores than expected. *See* Figure 2. While the CCS community considers the lack of demonstration projects an impediment to technology deployment, they perceive it to be less significant than many prior studies suggest. Likewise, although concern over public resistance to CCS projects has been cited as an obstacle to CCS deployment (Stigson et al., 2012; WRI, 2008), the CCS community scored this low on the scale of possible barriers. Lack of concern over public resistance may reflect the public's limited knowledge of CCS or the technologies involved (Curry, 2004). Alternatively, limited concern could reflect a belief that the risk associated with climate change outweighs any negative consequences associated with CCS (Anderson, 2007; Hansson and Bryngelsson, 2009), suggesting that opposition to CCS as a mitigation strategy is unlikely to develop.

Possible CCS barriers were ranked using the mean scores for each question. In all, five categories received mean scores indicating that they are perceived to be significant (mean scores greater than 3.50)[4] barriers to CCS deployment: CCS cost, uncertainty regarding climate change legislation (*i.e.*, the lack of a carbon price signal), CCS liability, the lack of a comprehensive

CCS regulatory scheme, and public resistance to CCS. As shown in Figure 2, with the exception of cost, respondents overwhelmingly see the largest barriers to CCS deployment as exogenous to CCS. That is, the difficulty with CCS is not CCS technology's feasibility but the "legal, policy, and economic considerations," as one survey respondent put it, that surround CCS.

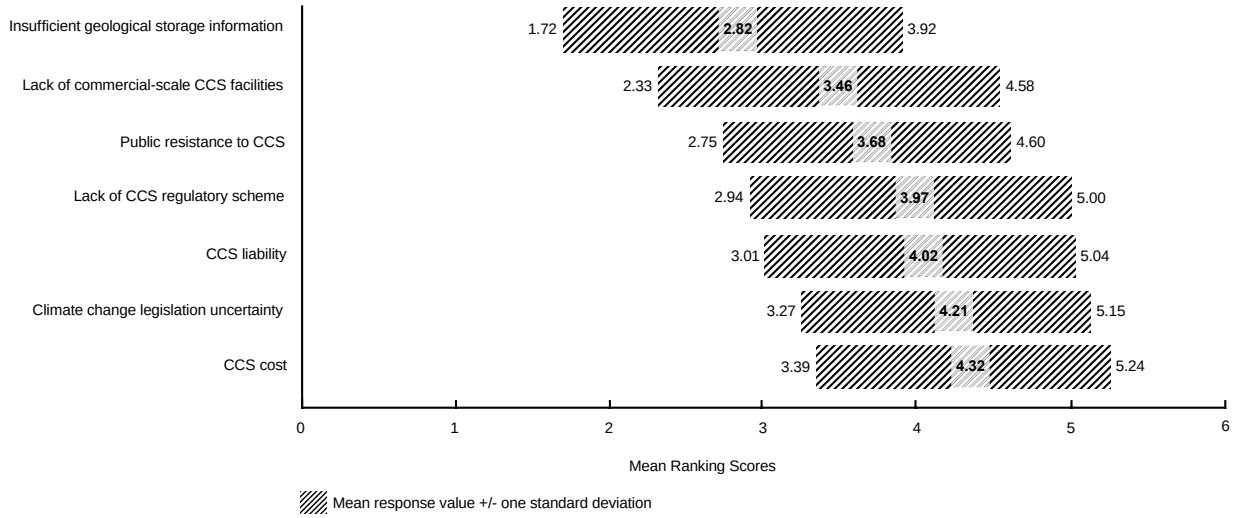


Figure 2: Mean Ranking Scores of Possible Barriers to CCS

The barriers that survey participants considered most substantial relate primarily to cost. Respondents repeatedly noted the cost of CCS, the lack of a carbon price signal or other incentives for using CCS, uncertainty regarding the ability to recover technology costs, and the risk of open-ended liability as the most formidable impediments to CCS deployment. One respondent said, "CCS costs money. [P]ut a cost on carbon emissions and then industry will figure it out. [It is] really that simple." This concern over costs comports with the results of earlier surveys identifying cost as the primary barrier to CCS deployment (Johnsson et al., 2010; Stigson et al., 2012).

Survey respondents also clearly crave regulatory certainty. The lack of "comprehensive" CCS regulation received a mean score almost identical to that for potential liability. This is understandable given the myriad permitting, siting, property rights, liability, rate regulation, cost

recovery, safety, and other legal issues that CCS presents. Thus, in response to the question "What is the most significant legal or policy barrier to commercial-scale GCS deployment?," one survey respondent answered: "Lack of the legal infrastructure necessary to support sound development of GCS, meaning long term responsibility management, [and] state and federal regulations . . . that address GCS implementation issues."

Figure 2's ranking of barriers to CCS commercialization was confirmed in two ways. First, the open-ended responses closely match the ranking responses. We compared the mean obstacle ranking scores for barrier "catchall" questions—those questions that asked about general categories of barriers, such as CCS cost or lack of a regulatory regime—against the percent of open-ended responses referencing one of the seven broad areas addressed in the catchall questions.[5] When asked to identify "the most significant" obstacle to commercial-scale CCS deployment, respondents' answers matched almost perfectly the order of the results to the ranking questions. In open-ended questions, the most cited obstacle to CCS commercialization was cost, followed by lack of a carbon price signal, CCS liability, and lack of comprehensive CCS regulation. *See* Figure 3. This was the same order of importance that survey respondents placed on these barriers in the ranking questions. The list produced from this open-ended question did, however, differ slightly in its ranking of the final three obstacle categories. As shown in Figure 3, respondents named public resistance to CCS least often in response to this open-ended question, whereas it was the fifth-highest ranked obstacle in the ranking questions.

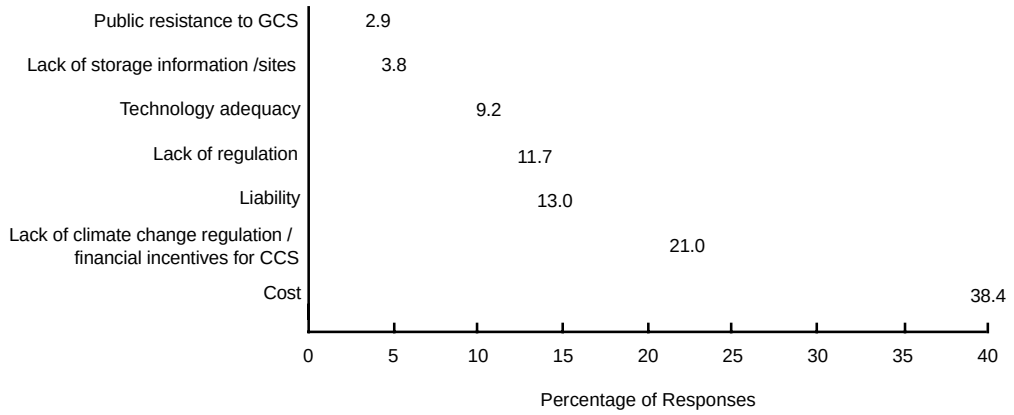


Figure 3: % of Open-Ended Responses Identifying Barriers as "Most Significant" to CCS Commercialization

Second, we compared the mean ranking scores of the broad catchall questions against the mean ranking scores for each of the subcategories in that category. For instance, while respondents ranked the catchall "cost of CCS" as an obstacle, they also ranked more specific but related obstacles, such as the "cost of CO_2 capture," the "cost of CO_2 storage," and the "cost of CO_2 transportation." The mean of these cost elements was compared to the mean of the catchall question, cost of CCS. Similarly granular subcategory questions were surveyed for each of the different broad obstacle categories.

This cross-check revealed an order of barriers similar to that of the catchall ranking questions. Although using the category-wide ranking scores dropped one obstacle, cost, from the first to the third most important CCS barrier, and raised another obstacle, the lack of comprehensive CCS regulation, from fourth to second, the overall pattern was nearly the same. Using the category-wide mean scores, the top four obstacles are the same as they were using either the catchall ranking scores or the open-ended answer percentages. The bottom three obstacles also remain the same. *See* Figure 4.[6]

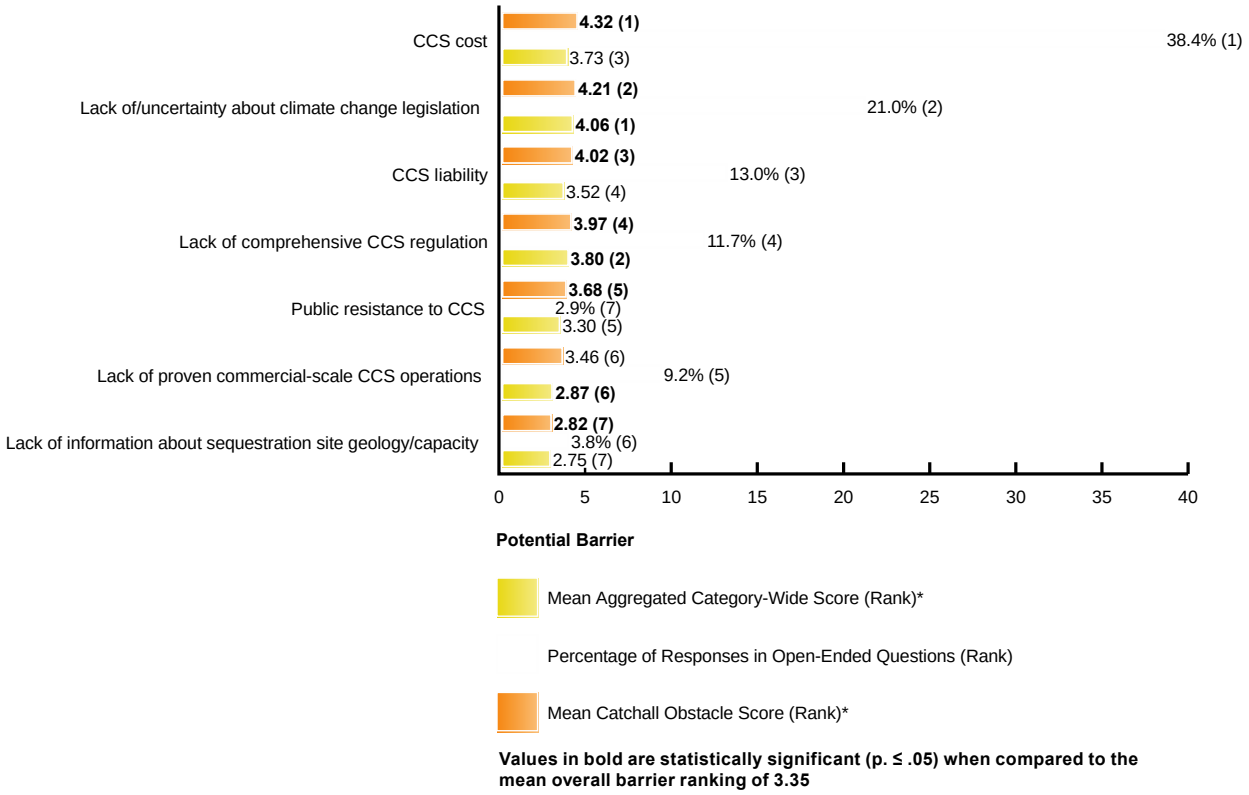


Figure 4: Comparison of CCS Commercialization Barrier Rankings

Notably, perceived obstacle importance varied little by the type of survey respondent. As shown in Figure 5, respondents from all demographic classifications placed the lack of a carbon price or other CCS financial incentive first when the category-wide scoring metric was used. Likewise, all respondent categories put CCS liability fourth as an obstacle and public resistance fifth. The only differences were that some respondent classes switched CCS cost and lack of CCS regulation between second and third, and regulators and researchers flipped the order of lack of CCS technology and insufficient CO_2 storage site information between sixth and seventh.

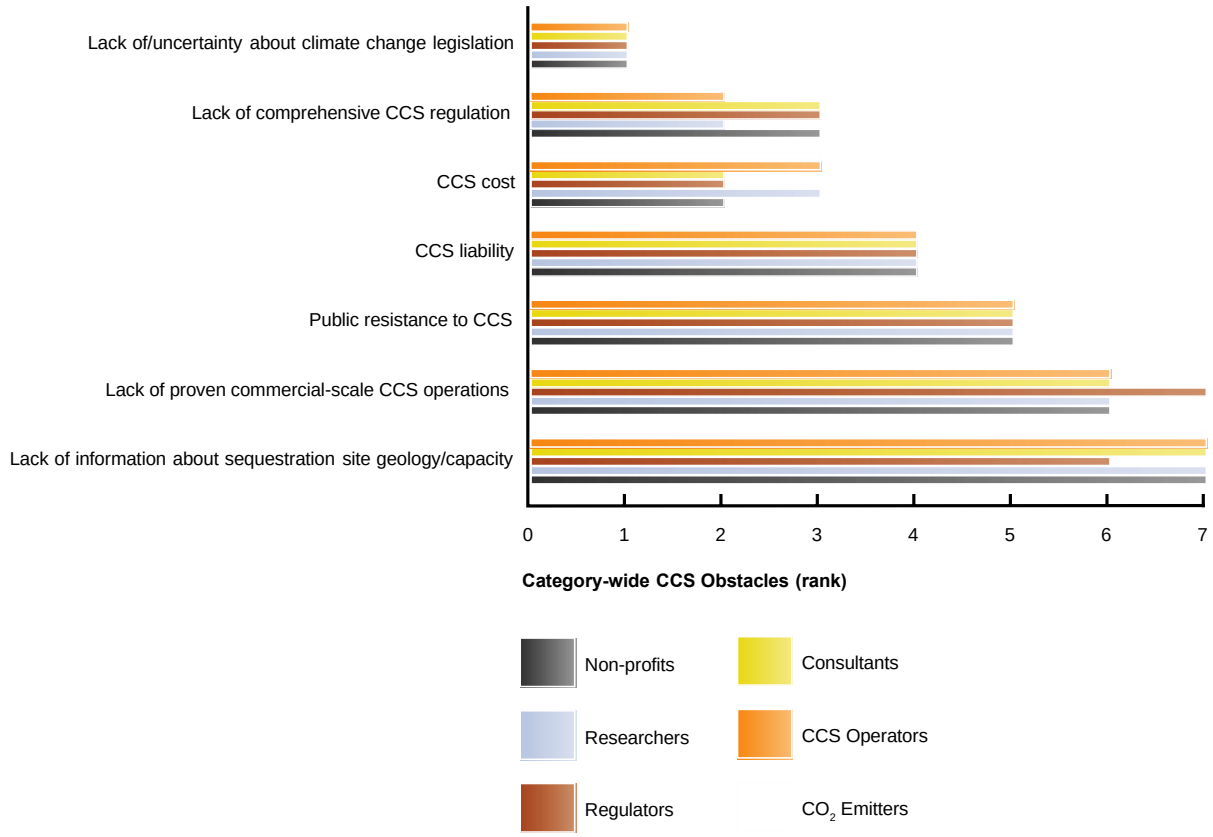


Figure 5: Obstacle Ranking by Respondent Category

Our results show that those who deal with CCS technology or policy on a daily basis rank barriers to commercialization differently than those who self-report as dealing with these issues only "occasionally." As shown in Figure 6, those who deal with CCS more often tend to view the lack of CCS regulation as more problematic than those who deal with CCS less often.[7]

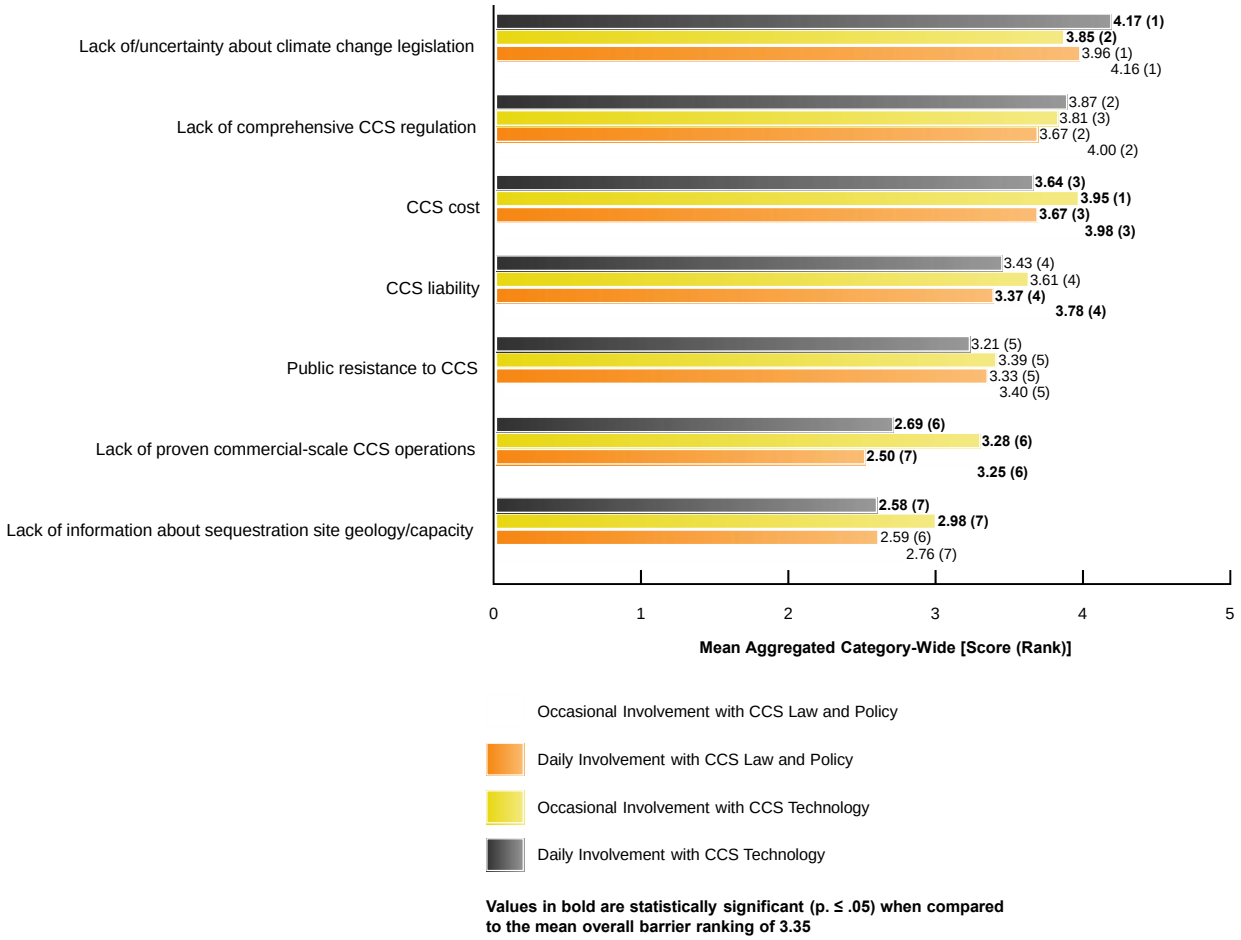


Figure 6: Mean Obstacle Ranking by Frequency of Involvement with CCS

The survey results revealed five additional findings of note concerning impediments to CCS. First, with respect to cost, it is primarily the price of CO_2 capture that the CCS community sees as an impediment to commercialization, rather than CO_2 transport or storage. This is largely consistent with the literature, which repeatedly has noted the energy penalty associated with CO_2 capture as a key driver for the relatively high cost of CCS (Der, 2010). In our survey, the cost of CO_2 capture received a higher mean score in the ranking questions (4.12) than any other factor except "the cost of GCS" itself. *See* Figure 7. Likewise, the "cost of retrofitting existing CO_2 emission sources" received the third highest mean score among six cost barriers (3.99). Open-

ended question responses reflected a similar pattern, with the cost of capture (22%) coming in second only to the cost of CCS generally (61%).

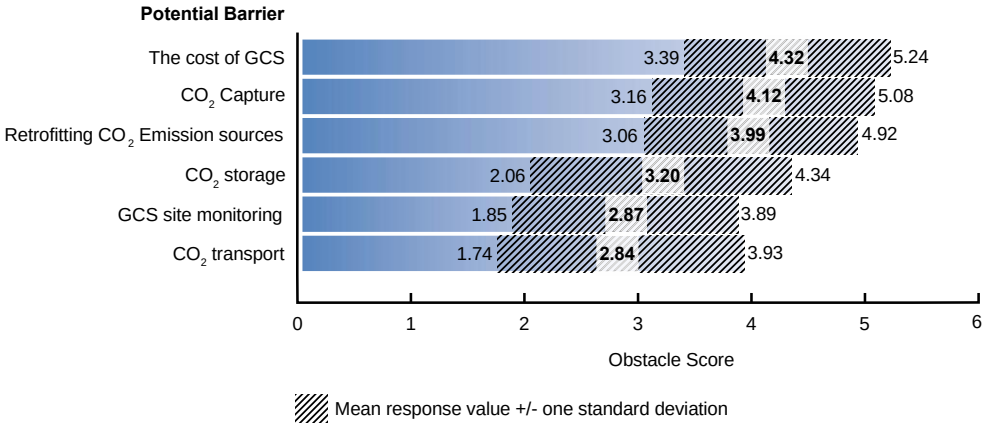


Figure 7: Mean CCS Technology Costs Obstacle Rankings

Second, also related to cost, survey respondents were more concerned about the uncertainty of CCS cost recovery than other CCS cost risks. Except for the cost of CO_2 capture, the options "public resistance to higher commodity and electricity prices," "uncertainty regarding utilities' ability to recover costs," and "public utility commission reluctance to pass along GCS costs to ratepayers"[8] received higher obstacle rankings than any other CCS cost element, including storage and transport. *See* Figure 8.

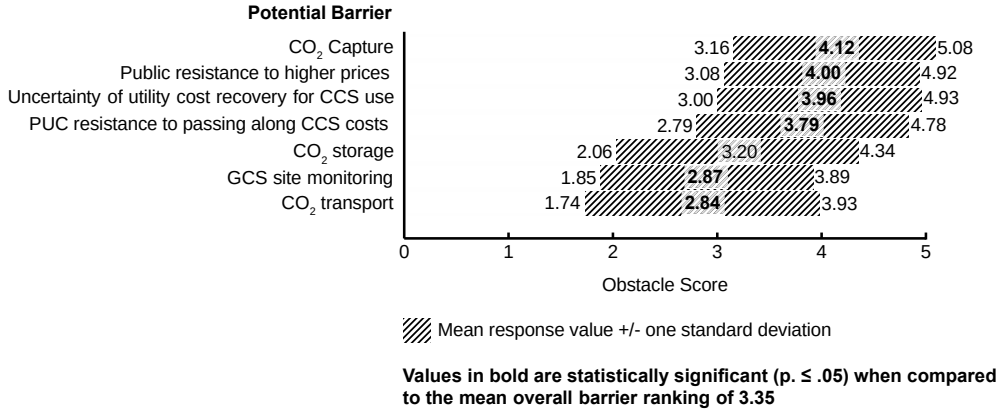


Figure 8: Mean CCS Cost Risks Obstacle Rankings

Third, with respect to liability, long-term liability of stored CO_2 is considered much more problematic than liability for CCS transport. The mean score for "liability for CO_2 pipeline operators" was 2.82. No other liability-related subcategory received a mean obstacle score lower than 3.43, and those for CO_2 storage liability and the lack of a statutory liability cap had means of 4.02 and 3.85, respectively. *See* Figure 9. This is consistent with responses to the open-ended questions. Of the 128 respondents identifying liability as a CCS legal or regulatory obstacle, 66% named some kind of liability related to CO_2 storage, 18% identified the lack of a regulatory regime alleviating liability concerns, and less than 1% of these responses pointed to liability associated with CO_2 transport as a CCS obstacle. *See* Figure 10.

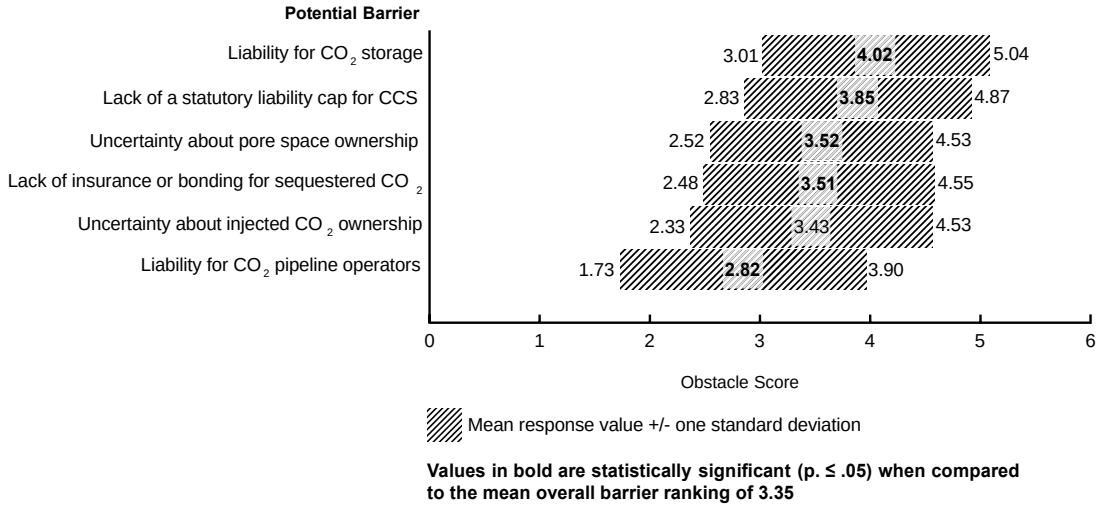


Figure 9: Mean CCS Liability Obstacle Rankings

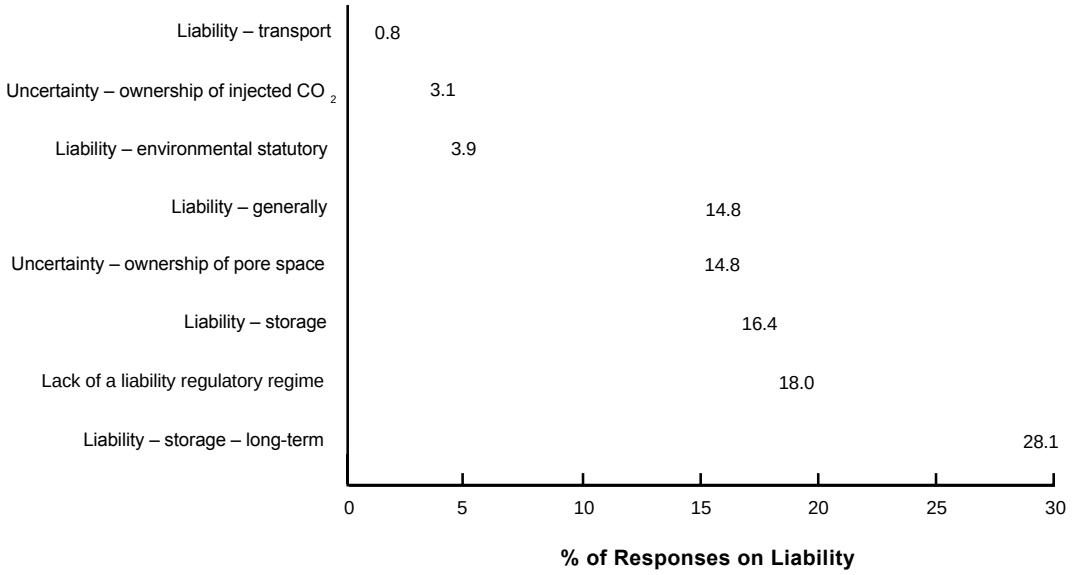


Figure 10: % of Open-Ended Responses Discussing CCS Liabilty T ype

Fourth, the survey data suggest that there is a possible disconnect between the feasibility of CCS technology and the risk that industry perceives in deploying it. That is, those familiar with CCS appear confident that CCS technology will work at a commercial scale, but parties are reluctant to be the first to assume the business risk of deploying it. The barrier "lack of proven commercial-scale GCS operations" ranked comparatively high as a CCS obstacle, receiving a mean catchall score of 3.46. *See* Figure 4. Yet barely six percent of responses to open-ended questions identified CCS technology inadequacy as the most significant "financial or business-related" obstacle to CCS use. *See* Figure 11. More importantly, of those responses, only 35% identified actual CCS technologies as inadequate—rather than merely pointing to a general lack of proof of successful commercial operations. Similarly, the barrier "inadequate GCS technology" received a notably below-the-mean score of 2.84. *See* Figure 4. This dichotomy is telling. It suggests a general industry confidence in the readiness of CCS technology but

hesitancy to deploy it on a commercial level. That reading of the data would be consistent with survey results underscoring CCS's cost as a primary barrier to commercialization, and inconsistent with continued calls for the need for commercial-scale demonstration projects before CCS can be deployed.[9]

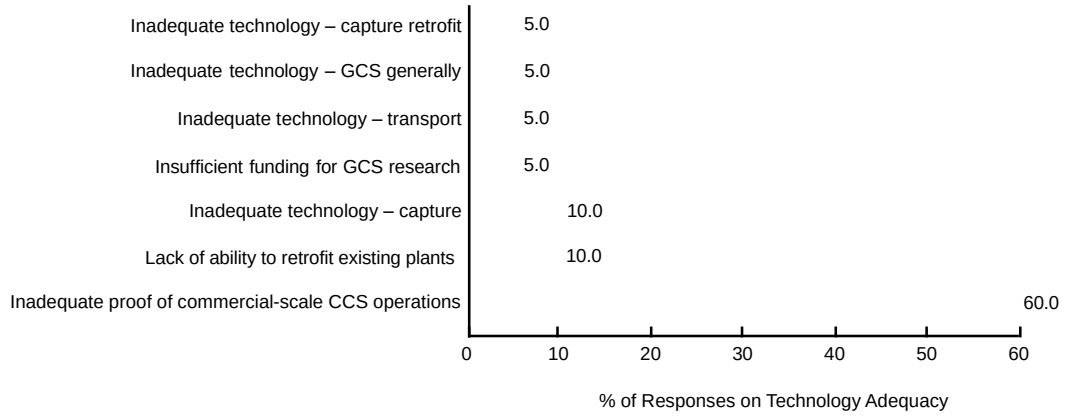


Figure 11: % of Open-Ended Responses Discussing CCS Technology Adequacy

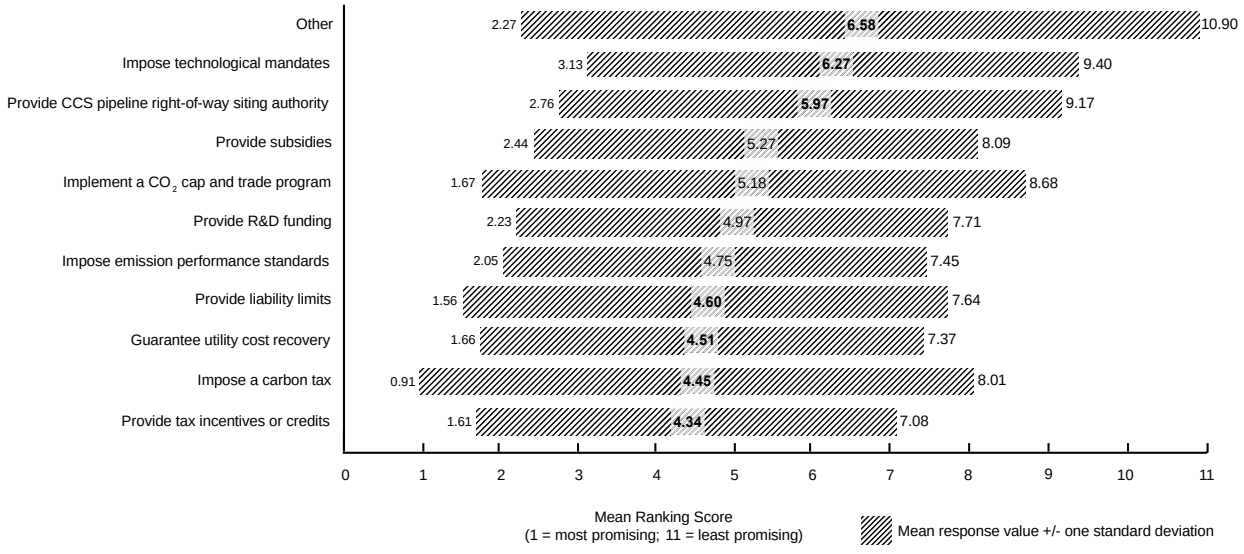
Finally, survey respondents appear confident that both storage capacity and geological information about potential sequestration sites is either available or obtainable. None of the possible obstacles listed under this category scored higher than 2.82, and all of them bunched between 2.66 and 2.82. *See* Figure 4. Lower concern over storage capacity was consistent with open-ended question responses, where just 3.8% of responses identified storage capacity as the "most significant" or "most significant legal or policy" barrier. *See* Figure 3.

4.2. Incentives for CCS Deployment

The survey data were more mixed on respondents' preferences for CCS incentives. The ranking data and answers to open-ended questions generated competing lists of the most preferred incentives. Likewise, analysis of the data makes clear that different sectors of the CCS community have different views on which incentives are best. In short, the survey results indicate that the CCS community desires strong government incentives for the technology—

some mix of tax/financial incentives, liability limits, a CCS regulatory framework, and a carbon tax—but there is no consensus on a single, "best" incentive for CCS deployment.

In the ranking question, respondents overwhelmingly favored policy incentives that address CCS costs. Respondents ranked eleven options for promoting CCS from "most promising" (1) to "least promising" (11). The most favored policy incentive was "tax incentives or credits," earning a mean score of 4.34. Close behind was imposing a carbon tax, with a mean score of 4.45. Following these options were cost recovery guarantees (mean score 4.51) and financial liability limits (mean score 4.60). The least popular option was mandating specific technology (mean score 6.27). Notably, cap and trade (mean score 5.18) was less popular than imposing a carbon tax. Aside from the value of "other" undefined incentives, imposition of a carbon tax and a CO_2 cap and trade program were the most controversial policy options, reflecting the highest degree of variation from the mean response. This may reflect the disproportionate media attention these policy options have received, though our survey provides limited basis for attributing causation. *See* Figure 12.



Values in bold are statistically significant (p. ≤ .05) when compared to the mean score for all preferred policy incentive questions (5.06.)

Figure 12: Mean Ranking Scores of Preferred Policy Incentives

However, the order of preferred CCS incentives changed when measured by responses to the open-ended questions, as shown in Figure 13. Using these responses, the need for CCS regulation dominated. Moreover, research and development funding moved up from sixth to third, as did the preference for technology mandates (from last to sixth). Suggestions of public education also emerged, and the weight placed on utility cost recovery measures plummeted (from third to last).

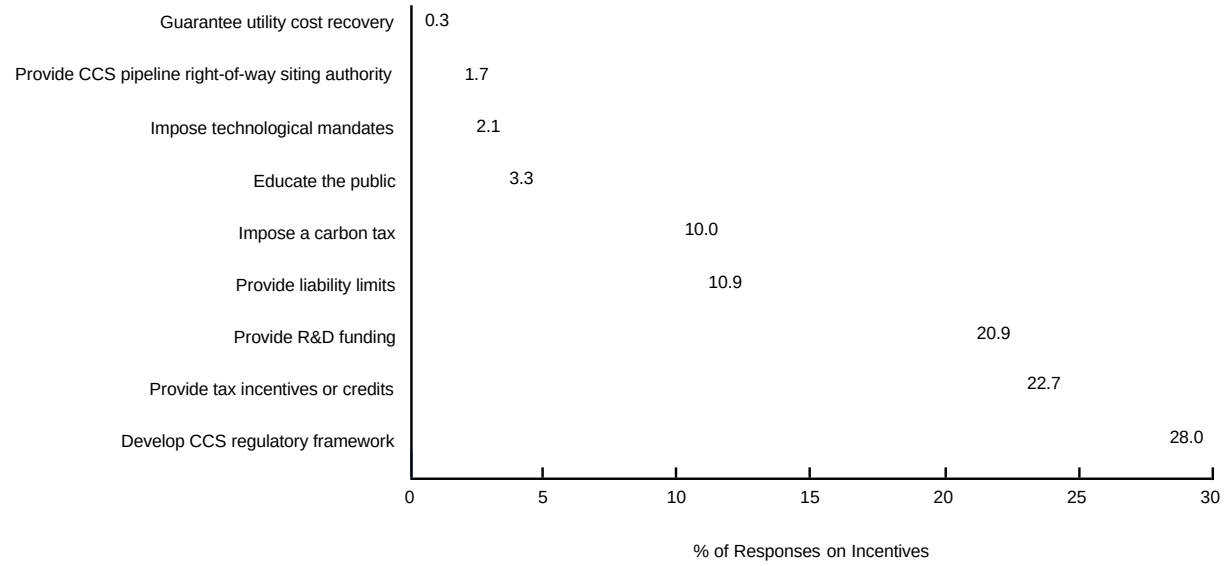


Figure 13: % of Combined Open-Ended Responses Identifying Preferred CCS Incentive

Moreover, respondents' preferred means of incentivizing CCS deployment varied by affiliation, as shown in Figure 14. CO_2 emitters and consultants prefer liability limits, while CCS facility operators prefer tax incentives or credits. Regulators prefer emission performance standards; researchers have a preference for a carbon tax; and non-profit interest groups prefer some other undefined option.[10] Interest in another, undefined option is notable because this was the least popular option overall in the ranking question and the last choice for CO_2 emitters, CCS facility operators, consultants, and researchers. Indeed, no policy option had a majority of

respondents rank it as either the most, or as the least, promising.

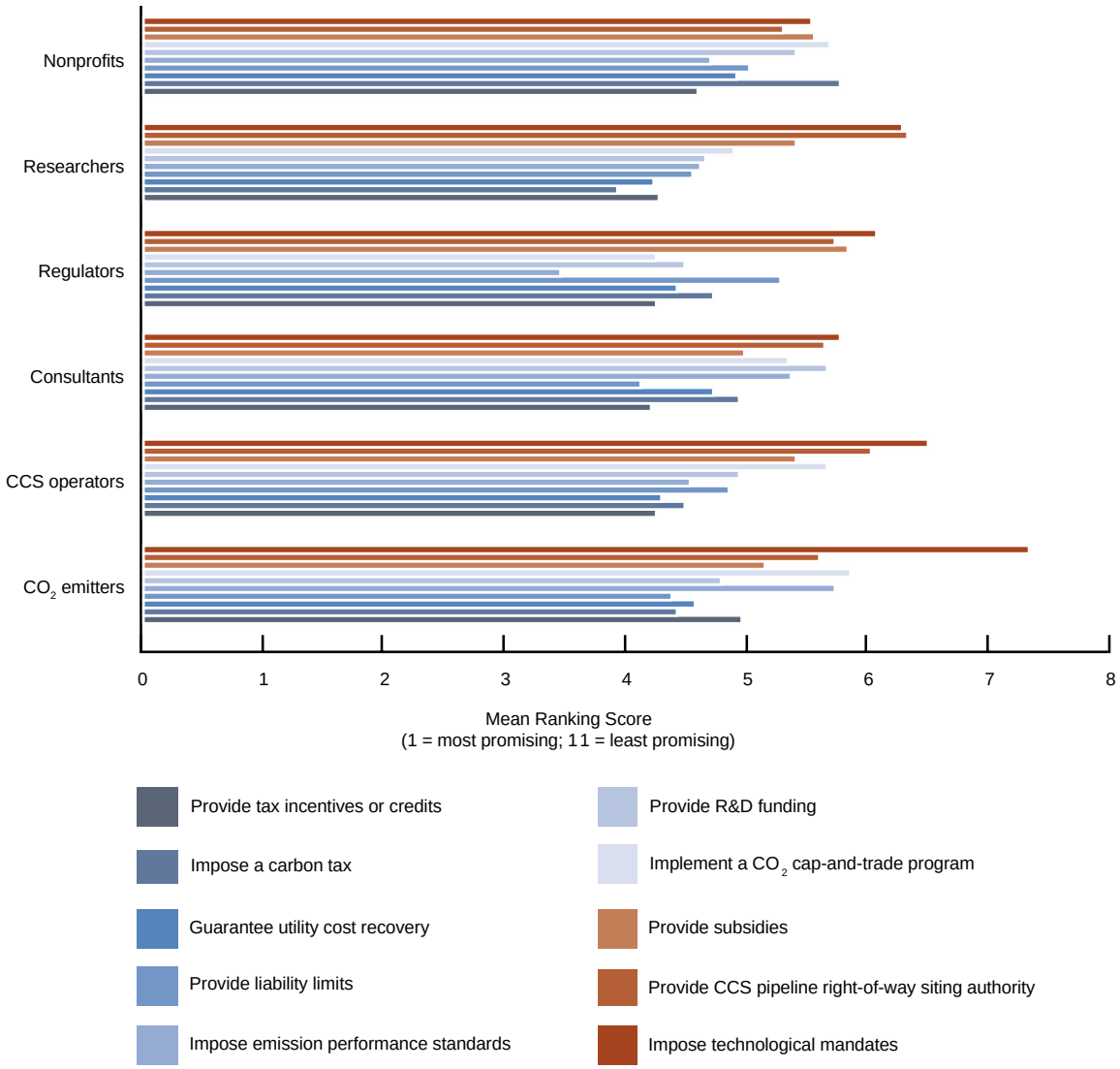


Figure 14: Mean Ranking Scores of Preferred CCS Policy Incentives by Respondent Type

4.3. CCS Policy Design

The survey responses also offer several lessons about what CCS regulation should entail. The first is related to the primary barriers to commercial-scale CCS deployment: The CCS community sees clarifying the regulatory landscape as one of the best ways to promote CCS use. Beyond this, respondents are most concerned about liability. Respondents also favor cooperative

federalism—that is, where the federal government sets regulatory limits that states flexibly implement—over other regulatory options.

The survey asked respondents to rate their agreement with several statements about the adequacy of existing CCS regulation on a standard 1-to-5 scale. Tellingly, no area of existing regulation received a mean rating lower than 2.5, or "agree." Instead, most areas earned neutral (2.50 to 3.49) mean rankings. As shown in Figure 15, those include transportation safety regulation, transportation ratemaking, transportation infrastructure siting, shipper access to CO_2 pipelines, CO_2 storage site monitoring, storage siting, and capture retrofitting. It is notable that respondents reported higher levels of confidence in existing transport regulations. One explanation of this may be the oil and gas industry's history of dealing with CO_2 pipelines and injection as part of enhanced oil recovery operations.

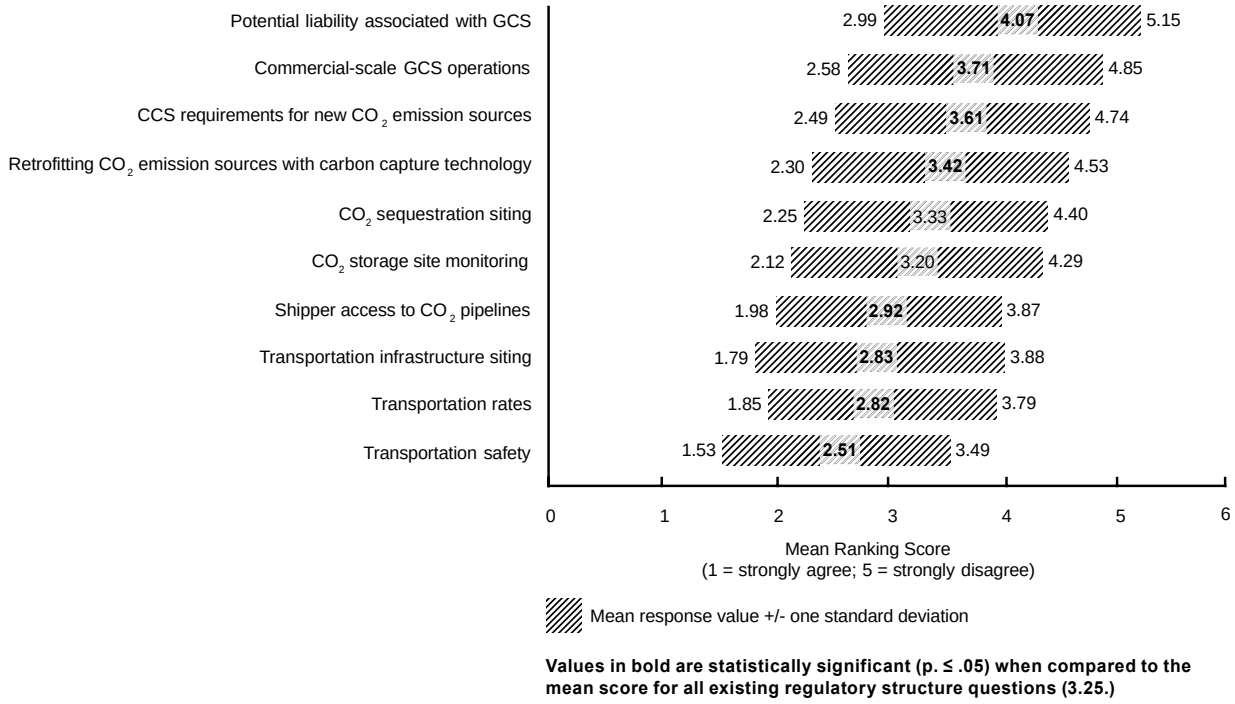


Figure 15: Mean Confidence Ranking in Existing CCS Regulatory Structures ("Existing legal structures are adequate to address . . . ")

By contrast, respondents expressed comparatively strong disagreement with the statement "Existing legal structures are adequate to address commercial-scale GCS regulations." This received the second highest level of disagreement among all the policy statements, with a mean score of 3.71. Only liability regulation ranked higher. This comparative displeasure with overall CCS regulation suggests a general need for a more comprehensive, certain, and transparent regulatory structure. Indeed, the need to develop a CCS regulatory regime accounted for more responses to open-ended questions than any other possible incentive. Regulation was mentioned in more than 30% of the responses to the query regarding the "most important" step that government can take to promote CCS. Statements such as "the lack of full spectrum legal and regulatory infrastructure that enables GCS" and "[i]t seems that regulations have not been set" were common responses to this question. When broken down by the type of regulation mentioned, over 16% of open-ended responses identified crafting comprehensive CCS regulation as one of the best ways to incentivize CCS use. The only more common answer involved limiting liability, which garnered 39% of responses. *See* Figure 16.

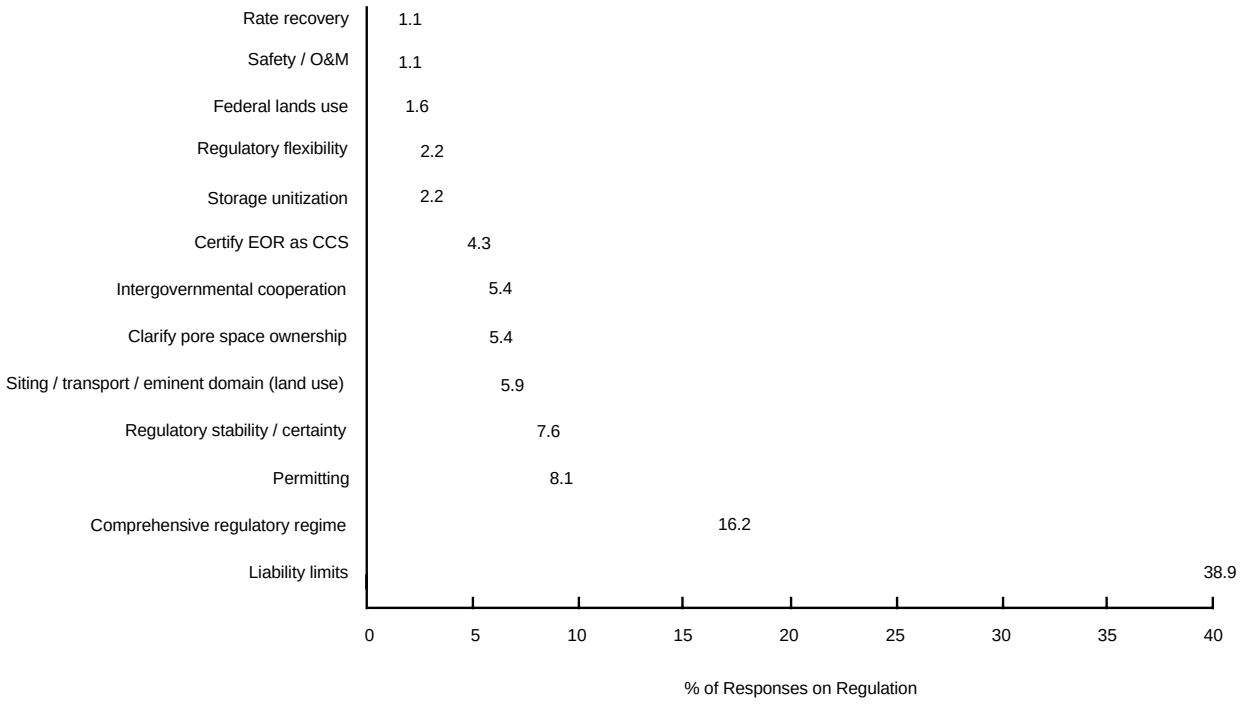


Figure 16: % of Open-Ended Responses Identifying CCS Regulation Area

Liability clearly was first on respondents' minds, whether looked at from the ranking or open-ended question data. As one respondent stated, "[T]he government needs to develop a way to take the long-term liability. No company is going to invest in an activity with liability in perpetuity. It's simply not a risk worth taking." However, the data were less clear with respect to the preferred type of liability reform. As Figure 17 shows, more than a fifth of responses called for federal custody provisions. If combined with calls for a liability-limiting law like the Price-Anderson Act (which was enacted to limit liability arising from major accidents for non-military nuclear power plant operators in an effort to incent private nuclear power production), long-term ownership of sequestered CO_2 and limits on liability for its release account for nearly a third of all responses. After that, clarification of pore space ownership ranked highest, followed by much smaller percentages of respondents asking for limits on environmental statutory and site monitoring liability.

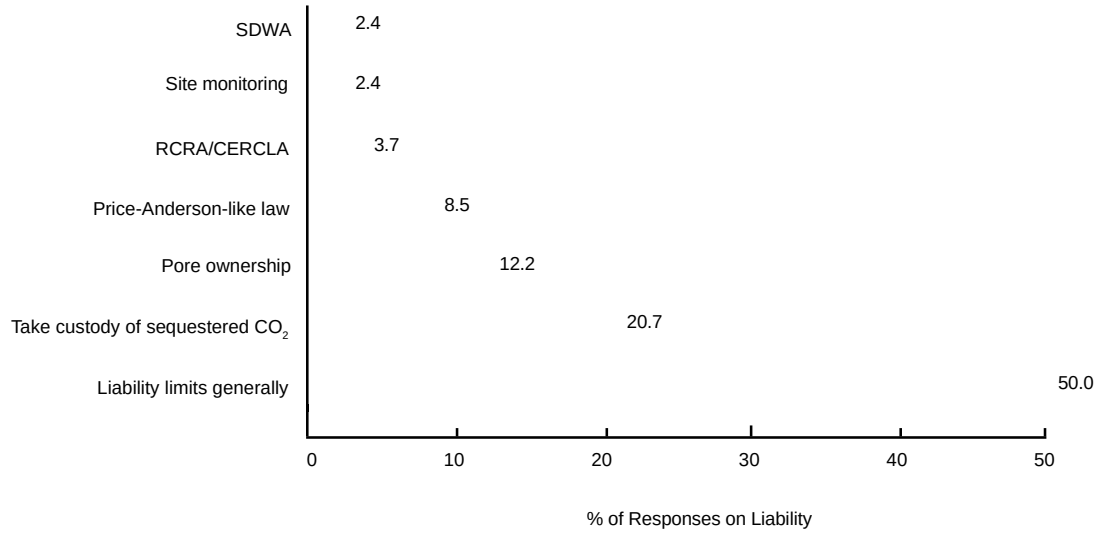


Figure 17: % of Open-Ended Responses Identifying CCS Liability T ype[6]

With respect to how CCS regulation should be implemented, two points emerge from the survey data. First, respondents favor cooperative federalism over an entirely federal or state-led approach. Ranking questions asked participants to score their agreement with using either federal or state primacy, or a cooperative federalist approach, to regulate CCS. Cooperative federalism earned a mean rating of 2.35; ensuring consistency through federal regulation followed closely behind at 2.39; and state regulatory primacy came in at a solidly neutral 3.00. *See* Figure 18. These rankings were consistent with responses to the open-ended questions. *See* Figure 19.

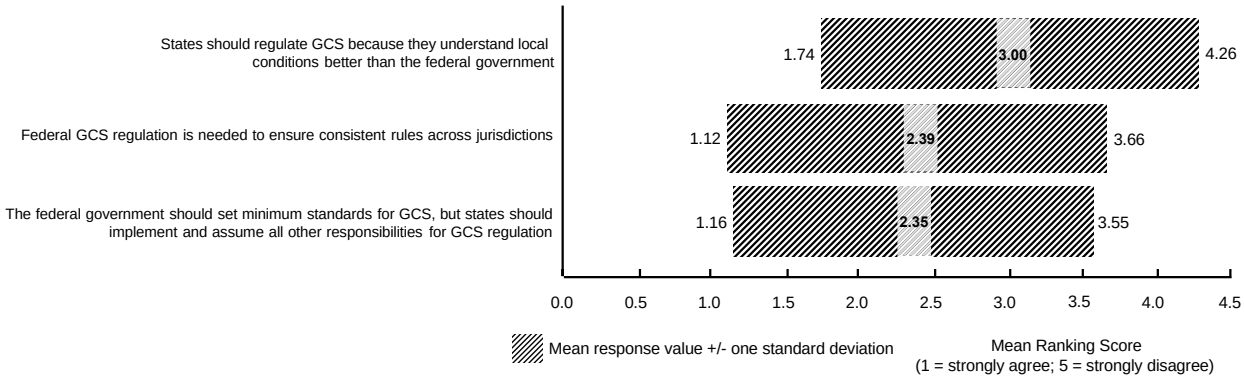


Figure 18: Mean Ranking Scores for Who Should Regulate

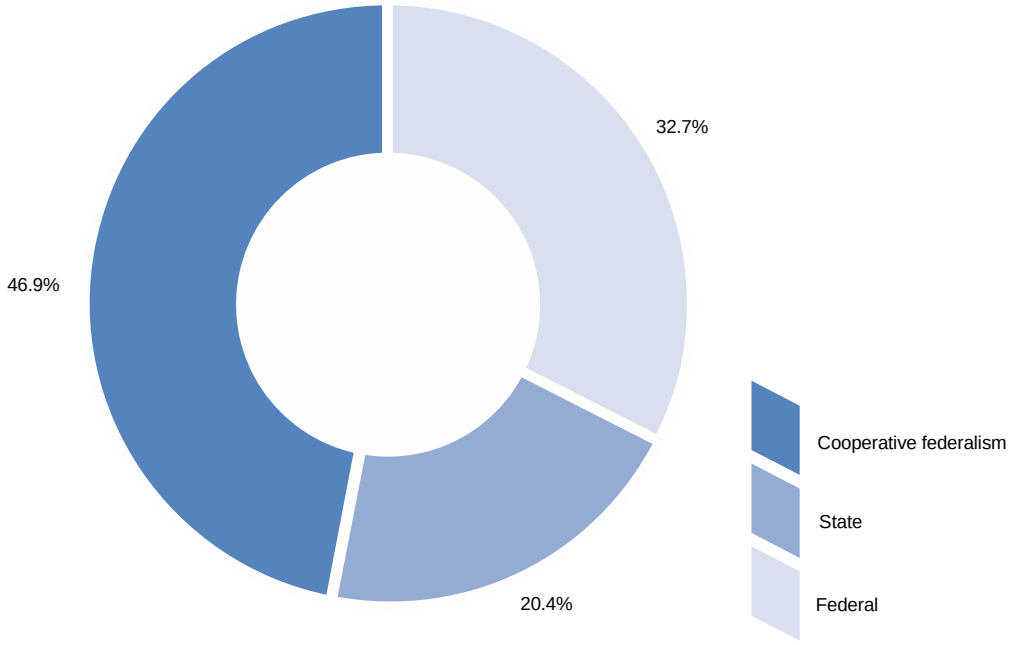


Figure 19: % of Open-Ended Responses on Who Should Regulate

Second, respondents prefer that regulatory primacy remain with the governmental entity already regulating the area. That is, although respondents favor cooperative federalism generally, they expressed a preference for maintaining areas of traditionally federal and state regulation. Traditional state and local issues such as permitting, rate recovery, and property rights (including pore space ownership), land use, and unitization received the majority of responses preferring state regulation. By contrast, areas of interstate and traditionally federal concern, such as off-shore CO_2 storage, pipeline rates and rules, and interstate transport, all received a much higher proportion of responses favoring federal regulation. *See* Figure 20. There were, however, two notable exceptions: (1) liability, and (2) safety/operation and maintenance of sites. Although both of these might be characterized as primarily local in nature, liability received a full 80% of responses identifying it as preferred for federal regulation, and site safety and operation and maintenance recorded 41.7% of responses in favor of federal control. These responses are

perhaps not too surprising given that safety and liability are closely related, and that a large-scale sequestration site failure could have far-reaching consequences.

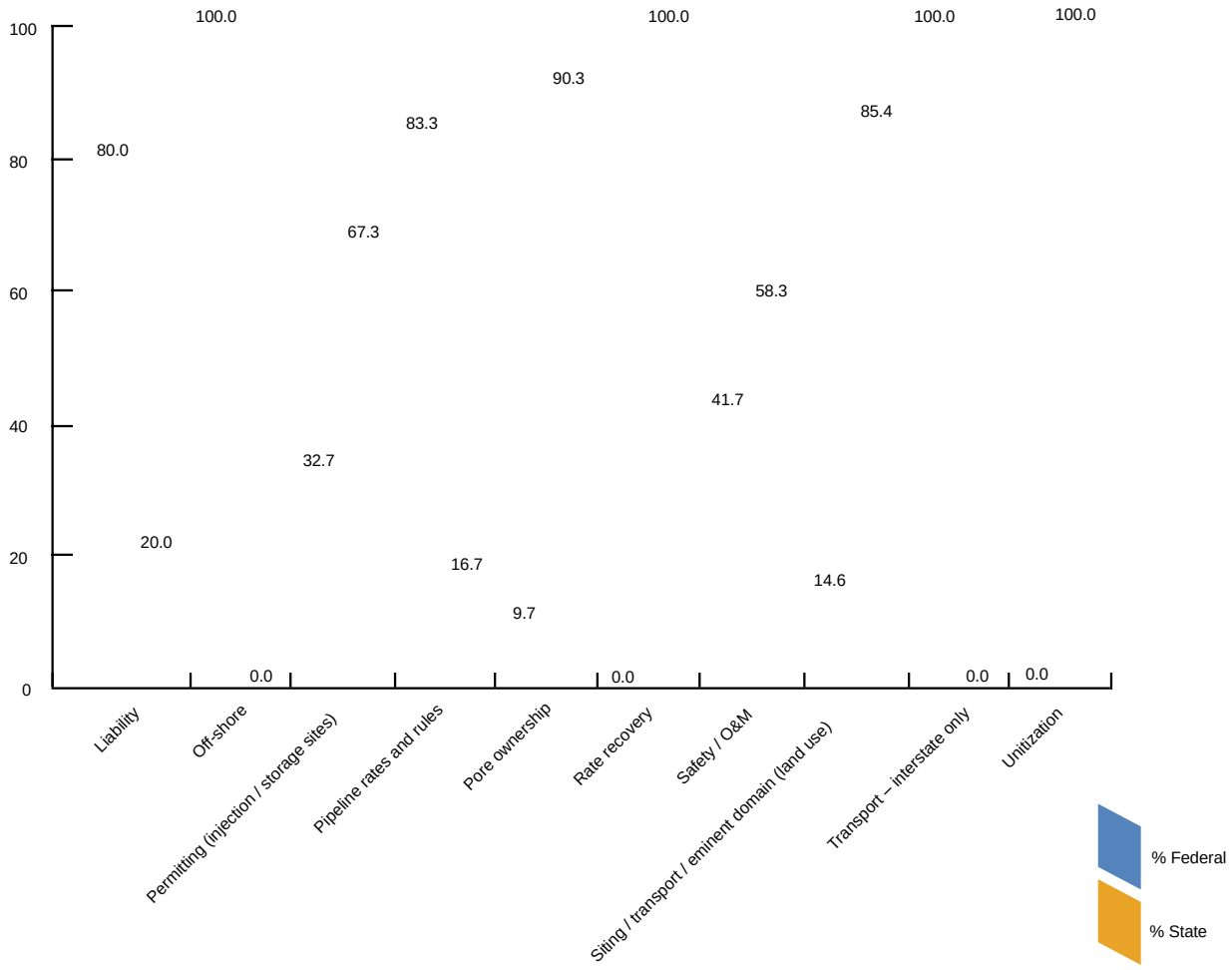


Figure 20: % of Open-Ended Responses Identifying Preferences on Who Regulates What

5. Implications—Shaping CCS Policy

If governments are going to address climate change, and if coal is to remain a dominant part of the global energy supply, CCS is a tool of potentially significant importance. CCS, however, like all emergent technologies, raises numerous critical policy questions, from how to support the technology to how to address the liability risks it poses. Policy success typically can be charted on the twin axes of efficacy and efficiency. On both scores, a greater understanding

of the pertinent issues can improve policy performance. For emergent technologies like CCS, stakeholder views have much to add to this conversation. Prior scholarship has made a number of suggestions for what CCS policy might look like, but with little quantitative basis reinforcing these views.

The data collected in our survey offer empirical insight into what the CCS community believes appropriate regulation of this climate change mitigation technology should include. Of course, what the CCS community believes would be ideal regulation is not necessarily synonymous with optimal policymaking. At the same time, however, when assessing the obstacles to, and governmental incentives needed by, emergent technologies such as CCS, the views of those most familiar with the technology must carry some weight. Compared against prior scholarship, the data provided by our survey thus suggests an initial blueprint for how the United States government might facilitate the transition to greater CCS use.

Our survey results confirm prior studies' suggestion that cost is one of the largest barriers to CCS commercialization. Thus, setting a carbon price or providing some other financial incentive for CCS use is an essential first step to CCS commercialization. These mechanisms must allow for the recovery of costs associated with CCS deployment. The absence of a price signal and investor reluctance to assume costs that are not mandated by government action led the list of concerns voiced by survey respondents. Without a sufficiently high carbon price or some other comparably strong inducement, CCS is unlikely to reach widespread commercialization. While this conclusion may be unremarkable to those familiar with climate change mitigation possibilities in the electricity sector, its importance is unmistakable.

Likewise, potential liability for CCS use must be addressed. Earlier literature and our survey results align neatly in their shared emphasis on CCS liability concerns. Both identify

potential CCS liability as a major impediment to CCS deployment. This is particularly true for long-term liability of stored CO_2, as opposed to shorter-term accidents or CO_2 leaks.

In addition, the CCS community wants comprehensive regulation for CCS implementation—not rules eked out one at a time, statute-by-statute, or state-by-state. Given industry's general desire for certainty (Boute, 2011; Fouquet, 2012; Rickerson, 2007), this desire for a comprehensive regulatory regime makes sense, but it has not been a consistent focal point of prior literature. Indeed, many prior studies focusing on the United States tend either to assume that the existing regulatory framework will suffice until CCS scales-up to widespread deployment (DOE, 2010), or to focus on narrow legal questions rather than treating CCS holistically (Carbon Capture and Storage Technologies Hearing, 2008; Chestney, 2009; DOE, 2010; Flatt, 2009; Freudenthal, 2008). This is thus one of the most important messages of the survey results: The CCS community craves regulatory certainty, and certainty requires comprehensive, integrated legislation.

Our survey data reveal not only that the CCS industry wants a comprehensive, predictable regulatory regime, but also what that regime might look like. Ideally, according to the survey responses, CCS regulation will rely heavily on cooperative federalism: with the federal government setting applicable standards and states implementing them in ways that reflect local conditions. Nearly 47% of survey respondents indicated a preference for cooperative federalism in CCS regulation. When considered along with the additional 33% of respondents who favor federal regulatory control, it should be clear that the CCS community supports a strong federal role of some kind. More specifically, areas favored for federal regulation include interstate CO_2 transport, pipelines, liability, and all aspects of offshore CCS.

Areas favored for state regulation relate to property rights, including pore space ownership, mineral rights unitization, and eminent domain.

With respect to shaping CCS liability policy, prior scholarship has considered a wide range of approaches (Carnegie Mellon, 2009; IOGCC, 2007), with no single liability framework emerging as the clear favorite (Carnegie Mellon, 2009; Flatt, 2009). Our results, however, suggest that the CCS community believes that eventual government custody of sequestered CO_2 is a necessary component of any liability regime. Over 40% of survey participants who identified a specific liability limit in their open-answer responses favor this approach. This position adds to the recommendations of the Interagency Task Force on Carbon Capture and Storage, which characterized government custody as only one of four possible approaches to managing long-term liability (DOE, 2010). According to our survey results, the next most favored liability approaches would address pore space ownership, cap liability akin to that for nuclear power operators, limit statutory environmental liability, and clarify long-term site monitoring requirements.

The divergence of our findings and the extant scholarly literature make plain a number of further, potentially important lessons for shaping CCS policy. Survey respondents ranked the lack of commercial-scale projects near the bottom of their list of concerns in CCS development. This stands in stark contrast to the scholarly literature, which long has suggested that large, commercial-scale projects must be completed in defined, sequential stages before CCS can truly get off the ground (Carnegie Mellon, 2009; GAO, 2008; Melzer, 2008). Contrary to this view, our survey suggests that the CCS industry is confident that the technology can be made fully operational today. This implies that calls for commercial-scale demonstration of CCS

technology may have more to do with investor confidence and social acceptance than engineering capacity and technological know-how.

Similarly, a number of prior studies have pointed to two potential barriers to CCS deployment that our survey results arguably discount: a lack of knowledge about CO_2 reservoir geology and plume movement (IPCC, 2005; IRGC, 2008), and public discomfort with CCS (DOE, 2010; WRI, 2008). These issues ranked quite low as possible CCS impediments in our survey. Knowledge of reservoir geology and capacity scored thirty-third and thirty-fourth out of forty-one potential CCS barriers, and lack of adequate sequestration sites scored thirty-sixth. While lack of public acceptance of CCS came in higher, at fifteenth, this ranking may reflect other concerns about CCS, such as its anticipated impact on electricity prices. Indeed, the mean obstacle values for the narrower categories of public resistance—to CCS storage facilities, transportation facilities, and capture technology—were much lower than the catchall public resistance score would imply: twenty-first, thirty-second, and thirty-ninth, respectively. This may suggest that the CCS community is not worried about public opposition to CCS *per se*, but rather, is apprehensive about the public's acceptance of regulatory costs. As those most familiar with the technology and its impediments, the views of the CCS community may be telling on this issue. Of course, it is also possible that the CCS community underestimates the level of public opposition to commercial-scale CCS deployment. Especially given that public resistance has proven a significant obstacle to many different kinds of energy projects in the United States—from off-shore wind farms to electricity transmission siting, from nuclear power plant relicensing to new coal facility permitting—public and interest group resistance to new CCS projects could prove significant, the CCS community's views notwithstanding. Indeed, regulation that accounts for public participation and involvement can lead to more robust, and lasting, success (Anshelm

and Galis, 2011; Davies, 1999). Thus, while efforts may be needed to address both the geologic knowledge gaps and public resistance to CCS, insofar as the CCS community is concerned, these barriers should not be among the first targets for government action.

Finally, our survey results add detail to a picture on CCS financial incentives that the literature thus far has painted only in broad strokes. Our results show that the CCS community most strongly supports four governmental incentives for CCS use: a carbon tax or price, liability limits, tax and other financial incentives, and a comprehensive CCS regulatory scheme. These incentive rankings dovetail with the dominant views expressed in the CCS literature, namely, that the absence of a meaningful carbon price (Der, 2010; Melzer, 2008) and clear liability limitations (Carbon Capture and Storage Technologies Hearing, 2008; Chestney, 2009; DOE, 2010; Flatt, 2009) stand as the most significant barriers to CCS. While no single, clear ranking of preferences emerged from the data, survey responses also show that the CCS community favors tax incentives, such as production tax credits, over numerous other possibilities, such as technological mandates, CCS subsidies, and R&D funding.

6. Conclusion

However limited the progress on broadscale CCS commercialization has been to date, the path toward deployment within the United States is clear. Comprehensive regulation and meaningful carbon pricing are essential if CCS is to move from promising prospect to commercial-scale implementation. In the absence of government leadership, the private sector is unlikely to assume the significant economic costs inherent in adopting CCS. On this score, our survey results lend greater detail to understanding the current barriers and incentives to domestic CCS deployment.

Carbon pricing and CCS regulation represent the most likely policy drivers. But in order to be effective, regulation must also address liability. The potential long-term liability associated with CCS creates uncertainty that most stakeholders believe necessitates federal legislation, with CCS stakeholders preferring either post-closure federal assumption of ownership, liability caps, or pooled risk similar to that undertaken for the civil nuclear power industry. CCS stakeholders also favor a regulatory framework under which the federal government sets nationwide standards but, similar to other federal environmental programs, allows states to assume primacy in administering the federal framework in a manner mindful of local conditions.

The more robust the framework for CCS utilization, the greater the likelihood that CCS can advance to the stage of being a meaningful policy tool. Hopefully, the granularity provided by our survey can help inform future proposals for the kind of CCS regulation that is needed to advance this important climate change mitigation strategy.

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[1] Our survey used the terms carbon capture and sequestration (CCS) and geologic carbon sequestration (GCS). The latter refers specifically to the land-based sequestration phase of CCS operations, while CCS sometimes refers more broadly to capture, transport, injection, and permanent sequestration in land- or non-land-based storage. To minimize confusion, this article uses CCS and GCS interchangeably.

[2] A copy of the survey is available at http://dx.doi.org/10.1016/j.enpol.2013.04.033.

[3] Two of the forty-one potential barriers were not coded into one of the seven general categories. Those were "public resistance to new coal-fired power plants," which received a mean score of 3.46, and "inadequate pipeline capacity for CO_2 transportation," which received a mean score of 2.81. These barriers were excluded because they are only indirectly related to CCS or did not align closely with the broader categories.

[4] Survey recipients were asked to rank 41 different possible barriers to CCS commercialization on a 1-to-5, with 1 representing "no obstacle" to CCS commercialization, 2 representing "minor" obstacles, 3 "measurable" obstacles, 4 "significant" obstacles, and 5 "critical" obstacles. A mean score of 3.5 or higher but less than 4.5 is thus considered "significant," because it represents the range at which the barrier ranking calculation rounds up from "measurable" to "significant" and, likewise, does not round up from "significant" to "critical."

[5] Percentages of responses to open-ended questions were calculated after blank, "don't know," and "other" responses (those that fit no coded category) were excluded. The number of "other" responses was minor. Where a response identified more than one obstacle, all obstacles were coded.

[6] The mean responses to the 41 specific barriers ranged from a low of 1.97 (technology to transport CO_2) to a high of 4.32 (the cost of CCS). Responses to the 41 barrier questions generated 7,510 individual data points, yielding a mean value of 3.35. The "Mean 'Catchall' Obstacle Score" and "Mean Aggregated Category-Wide Score" were tested for significant departure from the overall mean value of 3.35.

[7] Daily involvement with CCS technology was tested against occasional involvement with CCS technology, and daily involvement with CCS law and policy was tested against occasional involvement with CCS law and policy. Involvement with technology was not tested against involvement with law and policy.

[8] In many U.S. jurisdictions, state public utility commissions (PUCs) or public service commissions (PSCs) approve retail electricity rates. They do so to ensure that prices are neither too high (limiting impacts on customers), nor too low (ensuring utilities' ability to attract capital).

PUCs and PSCs also typically review utilities' investments to ensure they are prudent. By contrast, the Federal Energy Regulatory Commission (FERC) has jurisdiction over wholesale power sales.

[9] Prior research has identified a correlation between knowledge of a technology and favorable attitudes toward its deployment, both for CCS specifically and analogous industrial activities (Evar, 2011; Sala and Oltra, 2011; van Alphen, 2007). Several authors, however, have cautioned against overreliance on expert assessments, noting that experts may downplay concerns in the abstract (Evar, 2009) or underestimate public resistance (Bradbury et al., 2009).

[10] Self-identified non-profit representatives made up only 8% of survey respondents. While this group of respondents preferred "other" as the best way for government to incentivize CCS use, only three respondents specified what "other" meant. The remainder did not define this "other" governmental incentive.