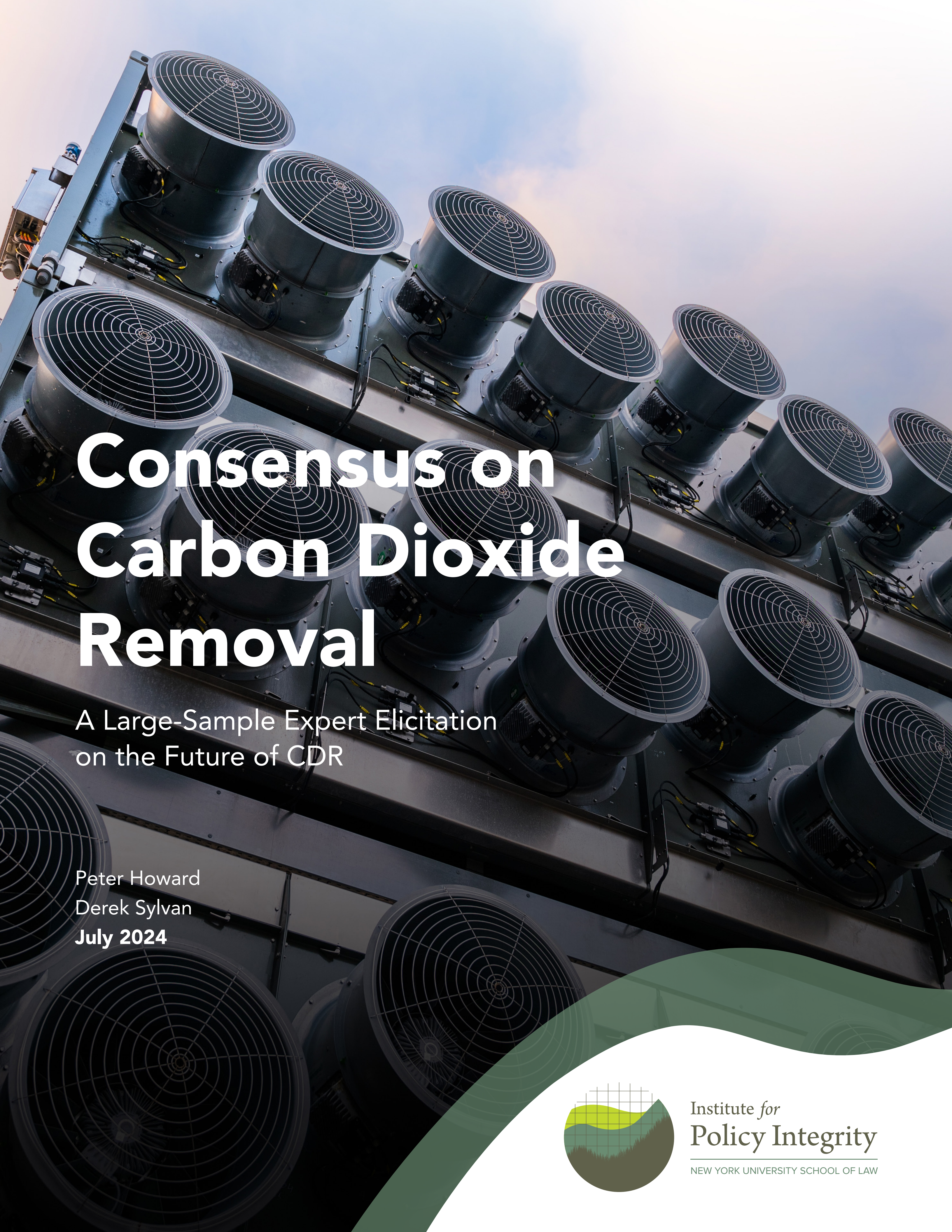


Consensus on Carbon Dioxide Removal

A Large-Sample Expert Elicitation on the Future of CDR

Peter Howard
Derek Sylvan
July 2024

Institute *for* Policy Integrity
NEW YORK UNIVERSITY SCHOOL OF LAW

Institute for Policy Integrity New York University School of Law
Wilf Hall, 139 MacDougal Street
New York, New York 10012

Derek Sylvan is the strategy director at the Institute for Policy Integrity at NYU School of Law, where Peter Howard, Ph.D is the economics director.

The authors thank Edgar Aguirre and Poorvi Hosabettu for helpful contributions throughout this project and Imaan Hilaly, Yue Guan, Alyssa Schiff, and Camille Steve for research assistance. Christopher Allen and Jason Schwartz provided valuable feedback. The authors also thank all participants in the expert elicitation for their valuable time and insights.

Cover photo © Climeworks. Climeworks' Mammoth plant, unveiling.

Table of Contents

Executive Summary

Many analysts project that large-scale, widespread carbon dioxide removal (CDR) will be necessary to reach net-zero greenhouse gas emissions, and thereby stop exacerbating climate change before United Nations temperature limits are exceeded this century. However, concerns about costs, technological constraints, safety, environmental justice impacts, moral hazard, and other issues contribute to tremendous uncertainty about the future of CDR. Expert elicitation—the process of formally eliciting the views of relevant subject matter experts to gain insight on complex or uncertain topics—can theoretically help clarify consensus on CDR-related issues.

We conducted an expert elicitation on issues related to CDR, surveying an interdisciplinary group of 699 researchers who had published at least one article on CDR in a leading academic journal. To our knowledge, this is the largest-ever survey of expert views on negative emissions. Our questions focused on topics including the projected cost and scale of various CDR approaches; key barriers and risks; and desirable policy options.

Our survey yielded forecasts and nuance that can complement data from the existing CDR literature. Some major findings are highlighted below.

- Our respondents predict that a long, diverse list of barriers will likely inhibit widespread CDR. They identify market costs and insufficient demand for CDR (due to government policy gaps) as particularly significant challenges.
- A number of policies could help pave the way for efficient, safe CDR. Respondents place particular emphasis on (direct or indirect) carbon pricing/demand-pull policies and R&D support. A combination of policies will likely be needed to overcome barriers.
- Despite numerous barriers and a dearth of current large-scale projects, respondents predict multi-gigaton-scale CDR to occur by 2050, with major additional growth through 2100. Our findings are more conservative than the CDR ranges determined to be technically feasible in the literature, but respondents predict a median of 2.3 Gt of CDR in 2050, 5 Gt in 2075, and 10 Gt in 2100. Mean responses are significantly higher due to a portion of respondents who offer especially bullish projections.
- Respondents predict that Bioenergy Carbon Capture and Storage (BECCS) will provide the largest share of CDR in 2075 (just over 20% of total removal), followed closely by forest-based CDR. They estimate that Direct Air Capture (DAC) will provide 15-20%, suggesting that they do not expect technological and cost concerns to limit DAC's ability to develop into a large-scale CDR option. Terrestrial and ocean-based approaches are also projected to play smaller but significant roles in 2075 CDR efforts.

- Once captured, respondents predict a mix of approaches for CO_2 storage or utilization in 2075. Underground storage or mineralization represents a plurality (roughly 40% of the total), with natural sinks, enhanced oil recovery, and utilization also projected to play sizable roles.
- Forest-based carbon removal is estimated to be the cheapest of all CDR approaches in 2075, with a mean cost of $49/tonne. Of the technological approaches, BECCS is projected to be significantly cheaper than DAC at a mean cost of $108/tonne compared to $163/tonne. DAC is the only approach with an estimated mean cost that exceeds the estimated mean cost of all CDR approaches in aggregate.
- Respondents' average cost estimates for all CDR approaches, including DAC, are significantly lower than prominent estimates for the social cost of carbon, suggesting that respondents expect all the CDR approaches discussed in this survey to be cost-benefit justified, at least by 2075. Moreover, we calculated respondents' projected marginal costs for reducing emissions in line with UN climate targets, and these are also lower than the social cost of carbon, suggesting that aggressive emissions reductions are cost-benefit justified.
- Nearly 48% of respondents believe that emissions-mitigation efforts would be significantly greater if widespread CDR does not become viable by 2075. This finding suggests a belief that society has the capacity to expand decarbonization efforts, and that the promise of CDR offsets is either a moral hazard limiting some emissions reductions or a lower-cost pathway that could make some less-desirable mitigation efforts unnecessary.
- The vast majority of respondents predict that enormous levels of CDR will be needed to achieve a 2075 net-zero GHG scenario. More than 85% of respondents believe that more than 12 Gt of CDR will be needed, with some estimating a need for dozens or even 100+ Gt. In a separate question, respondents predict much lower removal amounts in 2075, suggesting that they do not expect society to reach net-zero emissions in 2075.
- Respondents believe that ambitious R&D funding can play a major role in accelerating the deployment timeline for technologies such as CDR. In a scenario where heavy R&D funding is added to an already historically aggressive carbon-pricing (or equivalent) policy, respondents estimate that net-negative global emissions would become feasible significantly earlier—potentially before 2050. They also project that ambitious R&D funding would considerably shrink the uncertainty and range of feasible timeframes for reaching net-zero emissions.

Safely and efficiently scaling up CDR efforts to the levels many researchers deem necessary will be an enormous challenge. Our findings offer information that analysts and policymakers can use to inform expectations and policies related to CDR during this process.

Introduction

Governments and corporations increasingly rely on carbon dioxide removal (CDR), also known as negative emissions, in their climate strategies. CDR entails the use of various natural, technological, or hybrid approaches to remove CO_2 from the atmosphere for sequestration or utilization elsewhere.[1] (CDR is distinct from carbon capture and storage (CCS), which reduces emissions from an industrial point source, but does not result in net removal of atmospheric CO_2.)

Many analysts project that it will be more expensive, and potentially impossible, to reach net-zero greenhouse gas emissions (and thereby stop exacerbating climate change before United Nations temperature limits are exceeded this century) without large-scale, widespread CDR. For instance, the International Energy Agency projects that 10.4 gigatons of CO_2 must be removed annually by 2070 to offset energy-sector emissions in a net-zero scenario (IEA, 2020). (For context, global energy-related CO_2 emissions in 2023 totaled 37.4 gigatons.) Global CDR efforts are many orders of magnitude away from this level; the novel methods of CDR that are expected to play the largest roles in such scenarios currently remove roughly 0.0013 gigatons per year (Smith et al., 2024).[2]

Concerns about costs, technological constraints, safety, environmental justice impacts, moral hazard, and other issues contribute to tremendous uncertainty about the future of CDR. Not all CDR approaches will necessarily be viable or palatable on a large scale, and decisionmakers will benefit from a better understanding of the relative merits and potential drawbacks of different approaches. Such information is critical given that policy and investment decisions made in the near term will play a large role in determining the future cost and scope of CDR.

While research on various CDR approaches has expanded greatly, researchers offer a wide range of estimates on costs, constraints, and the expected scale of activities in the coming decades. The Intergovernmental Panel on Climate Change (IPCC), modelers, and other scholars have attempted to synthesize this research, but this is challenging given heterogeneous assumptions on technical, sociopolitical, and economic factors, as well as potential methodological biases.

Expert elicitation offers a potential solution, as it captures a wider range of opinions and clarifies areas of consensus. Moreover, through an elicitation process, each individual expert can offer their opinions independently and anonymously, avoiding groupthink and the pressures of social norms. Adding to this nascent literature, we conducted a large-sample online survey of experts who published on topics related to CDR in leading academic journals within the last five years.

---

[1] Prominent CDR methods are discussed in the following section.

[2] This category of novel CDR approaches includes Bioenergy Carbon Capture and Storage (BECCS), biochar, Direct Air Capture (DAC), and other approaches that go beyond conventional land management. Land-management-based CDR approaches such as afforestation currently remove roughly 2 gigatons of CO_2 per year, though these approaches may soon be limited by land-use constraints and other factors (Smith et al., 2024).

We received 699 responses from an interdisciplinary group of experts including engineers, scientists, and economists. To our knowledge, this is the largest-ever survey of expert views on negative emissions.

Our survey aimed to clarify expert consensus on the expected costs and capacities of various CDR approaches; likely timelines for deployment and growth; major constraints; and desirable policies.

We designed and beta-tested the survey to address anchoring bias, uncertainty, and forecast ability. The survey included 11 technical questions and forecasts, as well as specialization/demographic questions that allow us to disaggregate results. We finished conducting the survey in December 2023.

Our findings offer insights about expected future cost and deployment trends for different CDR approaches and sequestration or utilization options; key barriers and areas of uncertainty; and potential policies to address safety, environmental, and cost concerns. In addition to clarifying consensus around CDR, these results offer both direct and indirect insights on policies that could help make safe, efficient CDR expansion possible and avoid major risks.

Background on CDR Approaches

Carbon dioxide removal (CDR) refers to approaches that remove CO_2 from the atmosphere for sequestration elsewhere. These approaches are sometimes discussed as "negative emissions" in the academic literature. CDR approaches include human enhancement of carbon sinks (such as afforestation and reforestation, soil carbon sequestration, ocean fertilization, biochar, and enhanced weathering) as well as a variety of technological and hybrid natural-technological efforts (such as Direct Air Capture and Bioenergy Carbon Capture and Storage). Some of these approaches are described below, based on details from IPCC (2022), Minx et al. (2017), Minx et al. (2018), and National Academies of Sciences (2019). These descriptions generally reflect idealized processes to achieve negative emissions; some particular CDR approaches/projects may differ.[3]

- **Ocean-based carbon removal (ocean fertilization, alkalinity enhancement, coastal enhanced weathering, etc.)**: Biological approaches include cultivation of seaweed or microalgae that can sequester carbon in the deep ocean and management of blue carbon ecosystems with sequestration potential, such as mangroves and sea grass. Chemical approaches include ocean alkalinity enhancement that can increase CO_2 uptake and coastal enhanced weathering (such as the application of silicate materials in beach environments to convert atmospheric CO_2 into bicarbonate in the ocean). Some approaches combine biological, chemical and/or technological methods.[4]
- **Forest-based carbon removal**: Processes whereby CO_2 is sequestered in forests' above-ground biomass and soil. Primary examples include afforestation, reforestation, and silviculture, which stores CO_2 in wood-based products.
- **Other terrestrial carbon removal (soil carbon sequestration, biochar, enhanced weathering/mineralization, etc.)**: Examples in this category include agricultural practices that increase CO_2 sequestration in biomass and soil, such as "no tillage," and burying biochar (black carbon/charcoal produced from biomass). Enhanced weathering and mineralization efforts involve accelerating the natural processes by which various minerals absorb CO_2 and store it in the form of carbonate minerals, such as calcite or magnesite. This can involve the application of crushed silicate rocks or alkaline industrial waste products, such as steel slag. (Coastal enhanced weathering is often considered an ocean-based CDR approach.)
- **Bioenergy Carbon Capture and Storage (BECCS)**: The process of sequestering CO_2 in tree/plant biomass and then combusting that biomass to generate heat/electricity while

---

[3] Some CDR approaches may not fit neatly into these categories, while some projects may claim to meet the definition of CDR despite questions about achieving net-negative emissions on a lifecycle basis. Rigorous standards for monitoring, reporting, and verification (MRV) will be needed to ensure the integrity of CDR projects.

[4] Some recent projects have also used electrolysis of seawater to separate out CO_2 and increase future carbon sink potential.

capturing the resulting CO_2 emissions through technological means. The captured CO_2 emissions are then transported for geological storage or utilization and the biomass is regrown.

- **Direct Air Capture (DAC)**: Technologies that remove CO_2 directly from the atmosphere. Direct air capture systems use chemicals, such solid sorbents or liquid solvents, to separate pure CO_2 from ambient air. The CO_2 is then compressed for transport, geological storage, and/or utilization.

In our survey and in most of relevant literature, **Carbon Capture and Storage (CCS)** from an emissions point source is not considered carbon removal. CCS does not result in net removal of atmospheric CO_2 but instead reduces industrial emissions by capturing CO_2, usually from a power plant or industrial facility. The CO_2 is then compressed for transport, geologic storage, and/or utilization. The broader term **Carbon Capture Utilization and Storage (CCUS)** is sometimes used instead of CCS since captured CO_2 can be put to various beneficial uses in addition to being stored geologically. CCS and CCUS are sometimes used as blanket terms that include CDR, but we prefer the more precise separation of these categories.

CO_2 that is absorbed in a natural sink (forest, ocean, etc.) remains there for varying periods of time, depending on an array of factors. Technological or hybrid CDR approaches that capture CO_2 must then store it, usually either by injecting the CO_2 into geological reservoirs or using it in an accelerated mineralization process. Alternatively, carbon utilization efforts use CO_2 as an input in products or processes, such as the production of synthetic fuels, chemicals, or building materials. CO_2 is also frequently used in enhanced oil recovery, the process of injecting CO_2 into partially depleted wells in order to recover additional oil. However, even if the CO_2 remains sequestered, the resulting oil production and consumption can spur additional emissions.

The Utility of Expert Elicitation

Expert elicitation is the process of formally eliciting the views of relevant subject-matter experts to gain insight on complex or uncertain topics. This methodology can be particularly useful for clarifying parameters/values that are currently unmeasurable, but which could theoretically be measured and for which experts can observe related information (Howard and Sylvan, 2015, 2021). Eliciting the views of experts in a field can improve understanding of complicated issues and highlight prevalent points of view that might not otherwise stand out; this can help inform research as well as policy and investment decisions. Expert elicitation is distinct from public opinion polling, which is useful for gauging widespread sentiments and political views.

Policymakers and researchers regularly use expert elicitation to improve understanding of topics related to climate change. In an effort to clarify consensus on climate issues, the United Nations established the IPCC and tasked it with providing a consensus-based, scientific view on the current understanding of climate change and related topics. Through the IPCC's deliberative review process, thousands of climate experts from across the globe assess the most recent scientific, technical, and socioeconomic information, and then synthesize their findings. The IPCC reviews the research of CDR experts, along with experts in many other fields.

However, there are drawbacks to the deliberative process used by the IPCC (and others) to identify consensus. Group deliberations can lead to "groupthink," sometimes causing deliberation processes to suffer from censorship and uniformity (Sunstein, 2005). Indeed, the IPCC has been criticized for moving too slowly and adopting only the "lowest-common denominator" conclusions, leading to overly conservative results that ignore more up-to-date viewpoints (McKibben, 2007; Oppenheimer et al., 2019). In fact, actual measures of sea-level rise have tracked the high end of the IPCC's projections, and the IPCC's past temperature predictions were shown to be low (Rahmstorf et al., 2007; Rahmstorf et al., 2012). In other words, the IPCC has tended to underestimate the rate of climate change, and the results of its deliberative process may indicate only the minimal consensus in the scientific community—the *least* we can expect (Oreskes et al., 2019). IPCC publications on CDR, such as Working Group III's report (IPCC, 2022; Pathak et al., 2022), may suffer from similar estimation issues, though it will be difficult to determine their accuracy until CDR efforts have expanded and matured.

Besides deliberation, an alternate method for identifying the consensus opinion of experts is to use expert surveys and find a group's median or mean answer. Well-developed theories on "the wisdom of crowds" explain why the average answer from a group is likely to be more accurate than the answers of most individuals in that group, and why large groups perform better than small groups.[5] For example, groups of experts have been shown to significantly outperform

---

[5] In particular, the Condorcet Jury Theorem states that the probability of a correct answer by a majority of the group increases toward certainty as the size of the group increases, if each individual person is more likely than not to be correct (Surowiecki, 2004).

individual experts on predicting such uncertain quantities as the annual peak rainfall runoff of various countries or changes in the U.S. economy (Armstrong, 2001). By comparison, deliberating groups tend only to do about as well as their average members on making accurate predictions, and not as well as their best members (Gigone & Hastie, 1997; Marcoci et al., 2022).

Compared to deliberation, surveys can often produce a more nuanced understanding of expert consensus, and help reveal the full range of opinions in a group. Deliberation tends to reduce variance, since deliberations can amplify cognitive errors and overemphasize common knowledge, causing a group to converge on a common—though not necessarily accurate—answer. By showing the diversity of opinion, surveys can indicate where debate still exists on an issue and where a consensus might emerge. Surveys can also measure the level of uncertainty on a topic, which can be especially important for policymakers who are risk averse or who seek to maximize future policy flexibility.

Several CDR-related issues could theoretically be clarified by expert elicitation. While there is an existing body of literature with estimates for CDR costs, potential scale, barriers, and other issues, thousands of CDR researchers and practitioners with expertise in distinct but related topics may be able to provide additional insights on these issues that a literature review or small-group deliberative process might miss. Expert-elicitation findings can complement these efforts and help synthesize existing knowledge.

The Institute for Policy Integrity at New York University has conducted several expert-elicitation studies on climate issues in the past. In 2021 and 2015, we surveyed economists with expertise on climate change, eliciting their views on likely climate impacts and desirable policy strategies (Howard and Sylvan, 2021; Howard and Sylvan, 2020; Howard and Sylvan, 2015). Other researchers at the Institute for Policy Integrity conducted a similar study in 2009 (Holladay et al., 2009).

Recent Relevant Studies

Several previous studies, discussed below, have used literature reviews and small-sample expert elicitations to develop consensus estimates on CDR-related topics.

Expert-Elicitation Studies on CDR Approaches

Sovacool et al. (2022) elicited cost and scale estimates for several CDR approaches from 74 experts who represented "a mix of advocates and critics" of CDR.[6] Their survey examined the future potential of both negative-emission options and solar radiation management techniques. Over 90 percent of their respondents believed that negative-emissions technologies are necessary to reach climate targets. When asked to rank CDR approaches in order of their preference, respondents identified afforestation and reforestation, ecosystem restoration, and soil carbon sequestration as their preferred CDR approaches. Respondents also estimated the costs per metric ton (tonne) of CO_2 removed in 2050 for various approaches. Lower-cost approaches included afforestation and reforestation (median range of \$5–50 per tonne of CO_2, mean of \$27.50), soil carbon sequestration (\$0–50, mean of \$25), ecosystem restoration (\$0–87.50, mean of \$43.75), blue carbon and seagrass (\$0–75, mean of \$37.50), and biochar (\$20–100, mean of \$60). The respondents projected significantly higher costs for BECCS (\$75–200, mean of \$137.50), enhanced weathering (\$30–200, mean of \$115), ocean alkalinization or fertilization (\$50–225, mean of \$137.50), DAC (\$100–500, mean of \$300), and CCUS (\$50–200, mean of \$125).[7]

The respondents also estimated the following 2050 removal amounts (in gigatons) by approach: afforestation and reforestation (2 Gt median, 61.3 Gt mean), soil carbon sequestration (2 Gt median, 36.1 Gt mean), ecosystem restoration (1 Gt median, 36.0 Gt mean), blue carbon and seagrass (0.35 Gt median, 26.3 Gt mean), biochar (0.75 Gt median, 40.3 Gt mean), BECCS (2 Gt median, 48.8 Gt mean), enhanced weathering (0.75 Gt median, 13.4 Gt mean), ocean alkalinization or fertilization (0 Gt median, 58.9 Gt mean), DAC (1 Gt median, 38.1 Gt mean), and CCUS (1 Gt median, 24.6 Gt mean). These mean estimates are dramatically higher than our respondents' projections and other estimates in the literature, with 2050 removal amounts that vastly exceed total global emissions. This seems to reflect some major outlier projections that were not trimmed/excluded. The selection criteria for respondents may also have favored some particularly bullish participants.

---

[6] The authors selected a pool of individuals who had published peer-reviewed research papers on negative emissions/solar radiation management, or published related patents and intellectual property. The detailed search and selection criteria for individuals to be included in the study are not fully explained in the final publication; the authors invited 125 individuals to participate.

[7] Some of these ranges include \$0 costs. Zero or even negative costs could potentially occur in the presence of a market failure, such as the existence of a positive externality (i.e., a social benefit) from learning-by-doing whereby current adoption lowers future costs (Goulder and Schneider, 1999). However, this study did not trim the data from respondents and may have selected potentially non-objective experts (i.e., "a mix of advocates and critics") without performance weighting, possibly leading to biased results.

Other expert elicitations have focused on specific CDR approaches. Bosetti et al. (2021) conducted an expert elicitation to assess 18 experts' projections for the future costs and impacts of liquid solvent and solid sorbent-based Direct Air Capture (DAC) technologies. They analyzed two scenarios: "Policy as Usual" (PAU) and a stringent climate policy aligned with the 2°C target (2DC). By 2050, experts anticipated that under the PAU scenario, liquid solvent-based systems will decrease in cost to a median of $275 per tonne of CO_2, ranging from $135 to $1150 per tonne of CO_2. Under the 2DC scenario, they expected these costs to drop further to a median of $214 per tonne of CO_2, with a range of $124 to $445 per tonne of CO_2. Similarly, for solid sorbent-based systems in 2050, the estimated median costs are $336 per tonne of CO_2, with a range between $158 and $631 per tonne of CO_2 under the PAU scenario. Under the 2DC scenario, these cost estimates decrease to a median of $214 per tonne of CO_2, with a range of $125 to $445 per tonne of CO_2. Experts, however, noted that changes in process design, energy sources, new materials, and more supportive policies could further reduce costs.

Rennert et al. (2021) used a small-sample, in-person survey to elicit projections of the potential scale of negative emissions over the next 300 years. Specifically, 10 experts on socioeconomic issues and climate policy provided quantile estimates for net emissions from natural carbon stocks and negative-emissions technologies for 2050, 2100, 2150, 2200, and 2300. The survey did not focus on CDR exclusively; it also asked for estimates of net emissions from land use, including potential negative emissions from forests and other carbon sinks, and potential positive emissions, such as those from wildfires. Combining the expert results using performance weights, Rennert et al. construct a distribution of "annual net CO_2 emissions from natural carbon stocks and negative emissions technologies". According to their most-likely path, net emissions from natural stocks and CDR approaches are jointly positive, and then decline towards zero by 2075 and become net negative for the rest of the century and thereafter. Even so, the wide 90th percent confident interval implies that net-positive emissions are statistically possible over this entire century and thereafter, though the distribution is right-skewed with the possibility of more than 10 Gt per year of negative emissions from these sources in 2075. This study differs from ours in several key ways: ours used a larger sample of experts, including a larger portion of scientists and engineers (the 10 respondents in Rennert et al. (2021) were experts in climate policy and socioeconomic issues); our survey included land-based CDR but not positive emissions from land; and we weighted all responses equally rather than employing performance weights based on respondents' accuracy on particular questions. (We plan to test how performance weighting affects our results in a future analysis, once outcomes are available for our near-term forecast questions; see the discussion for Question 11 below.)[8]

Vaughan and Gough (2016) conducted an expert elicitation to understand the real-world feasibility of rapid and widespread deployment of BECCS predicted in integrated assessment model (IAM) scenarios. The 18 experts they surveyed found that IAM scenarios use unrealistic assumptions regarding the extent of bioenergy deployment (available land, future yields, and proportion of bioenergy in energy mix) and the development of adequate societal and policy

---

[8] Our survey includes seed variables in Question 11 (soliciting near-term forecasts of events that will be verifiable in the near future, for purposes of weighting responses) but we are unable to apply them until outcomes become available later in 2024 or 2025.

support (policy frameworks, social acceptability, and efforts to ensure that BECSS results in net-negative emissions). However, their respondents judged IAM technology assumptions for CCS (with respect to technological limits and CO_2 storage dynamics) to be realistic.[9] The study identified uncertainty about bioenergy's contribution to net-negative emissions and societal impacts, including direct and indirect land-use-change effects on carbon, nutrients, and water, and appropriate regulatory frameworks, as significant constraints. The authors recommend considering only moderate BECSS scenarios feasible.

Major Reviews of CDR Cost and Deployment

Researchers have put forward a wide range of (often conflicting) forecasts of the potential costs and scale of various CDR approaches, partly based on their consideration of different assumptions and approaches. Only afforestation estimates are relatively consistent, as the cost of tree planting is well established (Minx et al., 2018). Estimates for BECCS, DAC, biochar, enhanced weathering, and other approaches can vary significantly, while ocean fertilization estimates have slowed due to concerns over "adverse side-effect, effectiveness and legal issues" (Minx et al., 2018).

Perhaps the most influential study of estimated CDR costs and scale—Fuss et al. (2018)—reviews the recent literature to assess the projected marginal costs and deployment details of several negative-emissions approaches in 2050 under favorable conditions (i.e., government support and limited shocks to the land sector). Fuss et al. then adjust the estimates from the literature to account for various factors, offering estimates for different approaches. Though the literature finds a wide range in marginal cost estimates for BECCS (from $15/tonne to $400/tonne), this range is narrower when considering real-world constraints and individual approaches. The researchers find a marginal cost range for BECCS from $100/tonne to $200/tonne with annual sequestration between 0.5 and 5 $GtCO_2$. For afforestation and reforestation, they place the cost range at $5/tonne to $50/tonne, though the annual rate of 0.5 to 5 $GtCO_2$ is based on biophysical limits, including the counter-productivity of the albedo effects of increasing boreal forests; this implies that forest-based CDR is more effective in warmer areas, which also happen to have lower land prices.

This study's initial cost estimates of DAC are high, from $600/tonne to $1000/tonne, driven by initial high fixed costs and lack of implementation experience, though marginal costs drop to between $100/tonne to $300/tonne under economies of scale likely in 2050.[10] The authors estimate DAC deployment of 0.5 to 5 Gt/year by 2050, though they note that this amount could increase to 40 Gt/year by 2050 if current limitations, such as limits to storage, are addressed.

The researchers find that weatherization (land and water) has a wide range of costs from $50/tonne to $200/tonne, though the costs could decline with economies of scale and may vary

---

[9] Moore et al. (2024), a more recent expert elicitation on the timescale for the development and approval of CO_2 disposal wells, finds that it will likely take 5 to 10 years to create and operate storage sites, implying potential delays for BECCS, and CDR more generally.

[10] Despite referencing marginal costs, Fuss et al. (2018)'s discussion of fixed costs indicates that its cost estimates reflect or are at least partially informed by average costs. (Marginal costs exclude fixed costs, while average costs include them.)

significantly depending on the specifics of the project (i.e., properties of rock used, transport distance, application details, and energy source), with adoption rates of 2 to 4 Gt/year in 2050 and thereafter. Ocean fertilization has a wide range of cost estimates from \$0/tonne to \$460/tonne. The authors do not provide a narrower assessment given the low feasibility of large-scale adoption resulting from low efficiency (due to high recycling of carbon) and consequential side-effects.

The researchers estimate the cost range for biochar at \$30/tonne to \$120/tonne,[11] despite the significantly wider range in the general literature (\$10 to \$345), due to lack of research and use at large scales. Given the limits to available biomass, the authors estimate the scale of this approach at 0.3 to 2 $GtCO_2$/year by 2050. Soil sequestration is the cheapest option, with estimated costs between \$0 and \$100/tonne in 2050. However, the feasible scale is limited to 2.5 to 5 $GtCO_2$/year, as not all land is available for soil sequestration (contrary to some model assumptions), and saturation occurs relatively quickly. If conservation practices are not maintained even after saturation, reversibility is also a serious concern.

For purposes of comparison with our results, we weight the Fuss et al. (2018) estimates by their projected potential scale. This overestimates aggregate potential due to some constraints, such as land availability, that apply across multiple CDR approaches (Minx et al., 2018). We find that Fuss et al. (2018)'s best estimate of average CDR cost in 2050 is between \$36/tonne and \$172/tonne, for removal of 6 to 26 $GtCO_2$/year. Due to the potential for forests, oceans, and other carbon sinks to reach saturation levels and reduce or cease absorption, all of the CDR approaches that augment existing carbon sinks will become less feasible over time (i.e., they will experience rapid increases in marginal costs).

---

[11] As another point of reference, Fuss et al., (2018) provide a mean cost estimate of \$90 to \$120.

TABLE 1.

Existing Literature Estimates of Annual CO_2 Removal Potential and Cost in 2050, by Approach

Based on Fuss et. al, (2018)

CDR Approach	**Potential Scale** ($GtCO_2$/year)				**Estimated Cost** (US$/$tCO_2$)			
	Fuss et al. Adjusted Estimates		**Estimates from the Broader Literature**		**Fuss et al. Adjusted Estimates**		**Estimates from the Broader Literature**	
	Low	**High**	**Low**	**High**	**Low**	**High**	**Low**	**High**
BECSS	0.5	5	1	85	$100	$200	$15	$400
DACCS 0.5–5	0.5	5	0.5	5	$100	$300	$25	$1000
Afforestation and reforestation	0.5	3.6	0.5	7	$5	$50	$0	$240
Enhanced weathering	2	4	0	100	$50	$200	$15	$3460
Ocean fertilization			0.5	44			$0	$460
Biochar	0.5	2	1	35	$30	$120	$10	$345
Soil carbon sequestration	2	5	0.5	11	$0	$100	-$45	$100
Total CO_2 removal / Average cost* (our weighted adjustments)	6	24.6	4	287	$36	$172	$4	$1,464

* *To estimate the potential range of total CO_2 removal, we aggregate the projected minimum and maximum Gt/CO_2 removed by each approach. However, this may represent an overestimate – Minx et al. (2018) highlights that this additivity may not be possible, as some physical and socioeconomic constraints apply across multiple technologies. To estimate average costs, we weight each CDR approach based on its projected percentage of total CDR deployment, assuming that the minimum and maximum estimates of potential scale correspond to the minimum and maximum estimates of estimated costs, respectively.*[12]

Other studies by prominent groups, such as the IPCC and IEA, rely on the Fuss et al. (2018) estimates for deployment and average costs for 2050, with minor changes. IPCC (2022) considers a wider set of technologies to estimate costs, though data is missing for most, with the exception of ocean alkalinity enhancement, for which deployment estimates range from 1 to 100 Gt/year by mid-century at costs between $40/tonne and $260/tonne. Consequently, the IPCC projects a higher removal potential for ocean-based CDR than the Fuss et al. (2018) estimate. Moreover, the

---

[12] By pairing the minimum potential scale and minimum cost estimates together (and likewise for the maximum scale and costs), we produce a more conservative (i.e., wider) estimate of average costs. However, it is more intuitive to pair the maximum scale with the minimum cost (and vice versa), which produces a range of $52/tonne to $156/tonne for the Fuss et al. (2018) author estimates and $10/tonne to $411/tonne for estimates from the broader literature.

IPCC implicitly assumes that current constraints on DAC, such as storage limits, will be addressed by 2050; it adopts Fuss et al. (2018)'s unconstrained estimate of deployment of 40 Gt/year. Similarly, IEA (2022) adopts the cost estimates for 2050 from Fuss et al. (2018), except that it lowers the cost estimates for BECCS to between $15/tonne and $85/tonne. In contrast, Fuss et al. (2018) rejects these lower estimates due to land constraints, particularly by mid-century when population pressures are expected to peak, adding to both land and sustainability limits.

Several other studies since the publication of Fuss et al. (2018) focus specifically on DAC, providing support for the idea that DAC costs are likely to drop significantly in the near future.[13]

---

[13] Examples include Realmonte et al. (2019) and McQueen et al. (2020).

Survey Design and Administration

Respondent Criteria

We sought to identify a pool of respondents from multiple disciplines with demonstrated expertise on CDR/negative emissions. Building on the approach used in prior expert-elicitation surveys by the Institute for Policy Integrity, we compiled a list of individuals who had published at least one article on these topics in a leading academic journal since 2017.

To compile our list of relevant academic journals, we consulted four peer-reviewed publications that analyzed the research in this field (H. Li et al., 2019; J. Li et al., 2019; M. Li et al., 2021; Wang et al., 2022). Using bibliometric and visual mapping techniques, these papers identified the academic journals that have published the largest number of significant articles in this area, as well as the most productive institutions and authors. Using these four reviews, we assembled a list of relevant academic journals. Our list included all the journals that were identified in at least three of the four reviews (*Applied Energy, Energy, Energy Policy, International Journal of Greenhouse Gas Control, Journal of Cleaner Production*). Given the predominance of engineering and natural science articles in these journals, we also included all identified journals with large numbers of articles by social scientists (*Climatic Change, Climate Policy, Energy Economics,* and *Nature Communications*). To further ensure an interdisciplinary mix of respondents, we also included all top environmental economics journals as identified in a similar literature review conducted for our previous expert elicitations on climate topics[14] *(American Journal of Agricultural Economics, Ecological Economics, Energy Economics, Environmental Resource Economics, Journal of Environmental Economics and Management, Journal of the Association of Environmental and Resource Economists, Land Economics,* and *Resource and Energy Economics*).

We next compiled a list of all researchers who had published at least one article related to CDR/negative emissions in one of these journals. We focused on articles published between 2017 and 2022 (2023 and 2024 lists were not complete at the time of our searches). We felt that this five-year span yielded an appropriately large list of researchers with up-to-date expertise.

We searched each journal for articles that contained relevant keywords related to CDR/negative emissions. We assembled our list of keywords from the four research-review articles mentioned above, which identified keywords used for those analyses, and we supplemented this list with additional terms commonly used in discussions of CDR in the literature. Using the Scopus database, we searched each journal for articles with any relevant terms in their title, abstract, or descriptive keywords.[15] After compiling a list of articles that met these criteria, we reviewed the articles for relevance, and gathered contact information for all authors/co-authors.

---

[14] See Howard and Sylvan (2021).

[15] We searched these journals in the Scopus database using our keyword list, with the following search algorithm: “Carbon capture” OR “Carbon dioxide capture” OR “CO2 capture” OR “Air capture” OR “CCS” OR “CCUS” OR “BECCS” OR “Carbon removal” OR “Carbon dioxide removal” OR “CO2 removal” OR “Carbon utilization”

After removing experts who had died and individuals for whom we could not locate a working email address, our review revealed 5,326 authors who fit our selection criteria. We divided this group into subsets based on the number of relevant articles they had published (one vs. multiple) and the type of journal in which they published (economics vs. interdisciplinary) so that we could compare responses from these subsets. Each group was sent an identical, anonymous survey. When analyzing the survey data, we compared the responses of these subsets as well as numerous other respondent subgroups based on academic discipline, category of CDR expertise, and other factors (based on answers to survey questions). Results are discussed below. In general, we found few major differences in subgroups' views and estimates, suggesting that our selection criteria did not lead to the inclusion of less-relevant respondents with divergent viewpoints.[16]

Survey Administration and Response Rate

We developed our survey questions and conducted several rounds of beta testing in order to refine survey design and question wording. We then conducted our survey online using Qualtrics software, with the survey open from November 8, 2023 through December 1, 2023. We sent each expert an email message that described the nature of this project, informed them of the reason for their selection, and requested their participation through an embedded hyperlink to the survey. Respondents were told that the survey would take roughly 20 minutes to complete, and that individual responses would be anonymous (the survey did not ask for any identifying information or track individual responses).[17] Respondents were sent three reminder emails that included deadline details. These emails were sent to the entire pool since we could not determine who had already completed the survey.

Of the 5,326 experts we invited to participate, 699 completed at least some portion of the substantive survey questions for an overall response rate of 13%.[18] Experts who had published more than one relevant article responded at a somewhat higher rate of 18%.

Issues with email spam filters likely affected the overall survey response rate, as we received a high percentage of bouncebacks from our invitation emails. For example, we received 535 bounceback e-mails from our final reminder message, representing an observable bounceback rate of 10%. The inclusion of the survey URL in the text of the invitation may have triggered some filters, though few alternate options exist for online survey administration.

OR "Carbon dioxide utilization" OR "CO2 utilization" OR "Negative emissions" OR "Carbon sequestration" OR "Carbon dioxide sequestration" OR "Carbon sequestration" OR "Geological sequestration" OR "underground sequestration" OR "carbon storage" OR "Carbon dioxide storage" OR "CO2 storage" OR "geological storage" OR "underground storage."

[16] Of particular note, we found that there was no significant difference between respondents with one relevant CDR publication and those with multiple relevant publications, across all questions.

[17] The exception was a subset of respondents who we identified for participation in a blue-ribbon panel, based on their larger body of relevant research. We gave these respondents the option to submit their name and email upon completion of the survey (this was not required).

[18] It is unclear from the academic literature what an "acceptable" response rate entails (Anderson et al., 2011). Sheehan (2001) found a 37% average response rate across 31 studies. However, there is strong evidence that e-mail survey response rates have been declining over time (Sheehan, 2001; Fan and Yan, 2010). Manfreda et al. (2008) found that the average response rate for 45 web surveys was 11% (Fan and Yan, 2010).

We responded to this high bounceback rate by increasing the number of email reminders, as we noted that there was some variation in which accounts sent bounceback emails from round to round.[19] Beyond the observable bouncebacks, some unknown portion of our invitation e-mails were likely stuck in experts' spam filters (one study analyzing online academic surveys found an undelivered rate of 28%).[20] To the extent that more aggressive spam filters are randomly distributed among our respondents, this issue is unlikely to bias our results, though it does increase the resulting variance due to the smaller sample size.[21]

Many respondents did not provide answers to every question, so the sample sizes and response rates differ by question.[22] Unsurprisingly, fewer people answered the more complex forecast questions, most of which were asked in the latter part of the survey when respondents may also have reached a point of fatigue. Overall, questions had sample sizes ranging from 226 to 687 responses.

TABLE 2.

Overall Response Rate

Pool of Invited Experts			Experts Who Completed at Least a Portion of Substantive Survey Questions	
Journal Type for Relevant Publication	**# of Relevant Publications**	**# of Experts**	**# of Respondents**	**Response rate**
Interdisciplinary	One	4065	468	12%
Interdisciplinary	Two or Three	695	110	16%
Interdisciplinary	Four or More	109	33	30%
Economics	One	440	82	19%
Economics	Multiple	17	6	35%
All groups		5326	699	13%

---

[19] We also received several e-mails in later rounds indicating that the candidate had not received an earlier invitation.

[20] See Ison, D. C. (2017).

[21] Ison (2017) noted that their survey response rate was impacted by the spam filters of particular institutions. Even if this is true, as long as the individual institutions are random and there are a sufficient number of them, bias should still not be an issue.

[22] Sample sizes for individual questions are provided in the analysis below. Roughly 5% of the invited experts responded to the initial survey questions about their background and expertise but did not complete any of the substantive questions.

Forecasting and Confidence Intervals

In an effort to reduce bias and solicit carefully considered forecasts, we asked respondents to provide confidence intervals for several questions. The academic literature on surveys encourages this approach (Cooke and Goossens, 1999). For survey questions that focused on future forecasts, we asked respondents to provide 5th and 95th percentile estimates as well as 50th percentile (most likely) estimates. We included this language in the survey questions: "To avoid overconfidence and anchoring biases, please fill out your 5th and 95th percentile estimates before providing the 50th percentile (median/most likely value). Also, please carefully consider the full range of possibilities and assess whether these events fall within or outside each of these confidence intervals." We also offered a link to an explanation of confidence intervals, and our initial forecast question used these descriptions:

- **5th Percentile** – 1 in 20 chance that true amount is below this value
- **50th Percentile – Most Likely Value** – 50-50 chance that true value is below or above this amount
- **95th Percentile** – 1 in 20 chance that true amount is above this value

Using this approach can theoretically prompt respondents to consider a broader range of factors and possibilities before settling on their "most likely" value. Our analysis of forecast questions below focuses primarily on respondents' 50th percentile estimates.

Contextual Information Provided

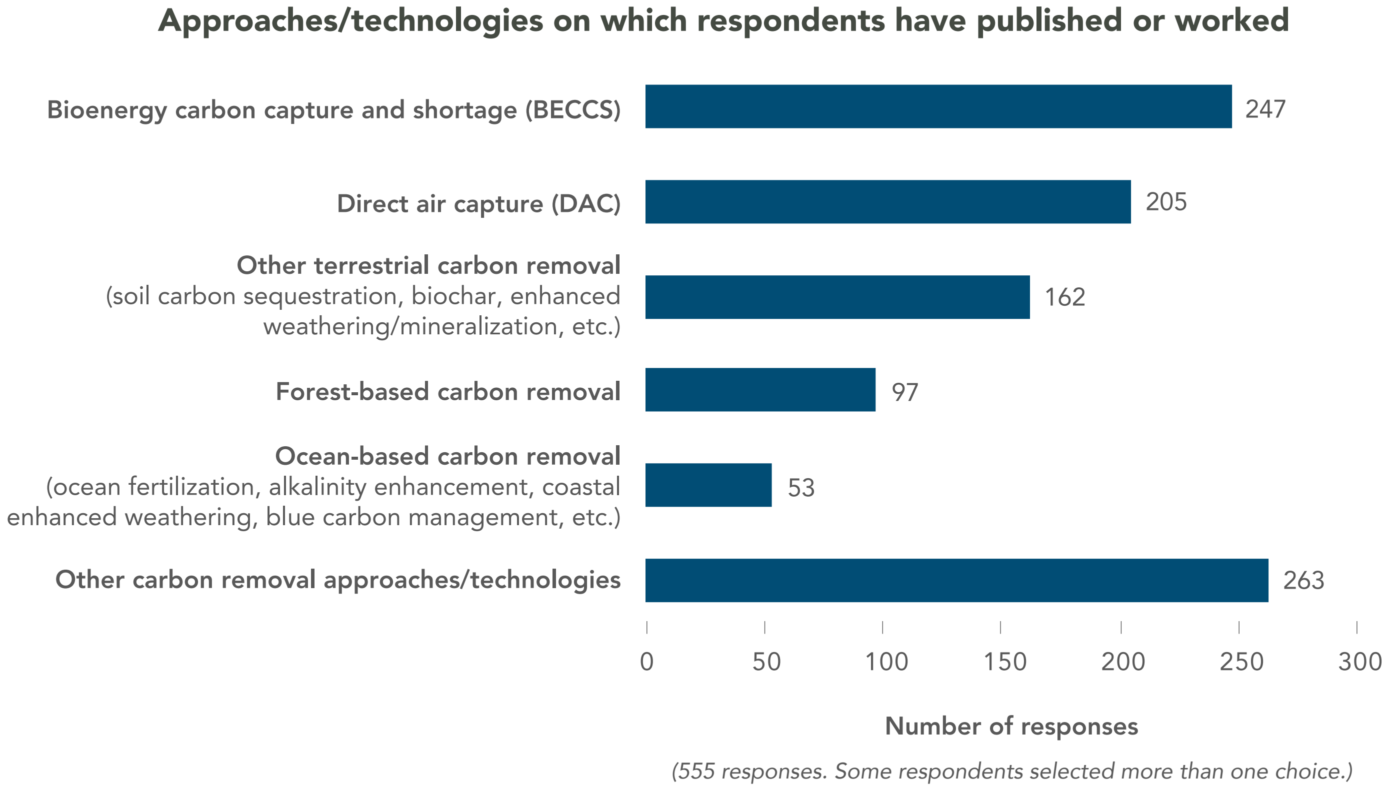
To ensure clarity, we provided links with definitions and context for technical terms, including all CDR approaches, climate scenarios and variables, and feasibility and cost terms. We also provided an overview of relevant statistical concepts. Respondents could access this information at any point during the survey, and links were included on all relevant survey pages.[23]

Respondent Details

We opened the survey with five questions about the respondents' backgrounds and areas of expertise. In addition to clarifying details about our sample, these questions allowed us to compare the responses of subgroups based on their specific expertise.

---

[23] The definitions and contextual information we provided in the survey can be found here:
CDR approaches: https://policyintegrity.org/documents/Definitions_of_Carbon_Removal_Approaches.pdf
Climate scenarios/variables: https://policyintegrity.org/documents/Climate_Scenarios_and_Variables.pdf
Feasibility and cost terms: https://policyintegrity.org/documents/Techno-Economic_Terms.pdf
Relevant statistical concepts: https://policyintegrity.org/documents/Statistics_-_Confidence_Intervals_and_Percentiles.pdf

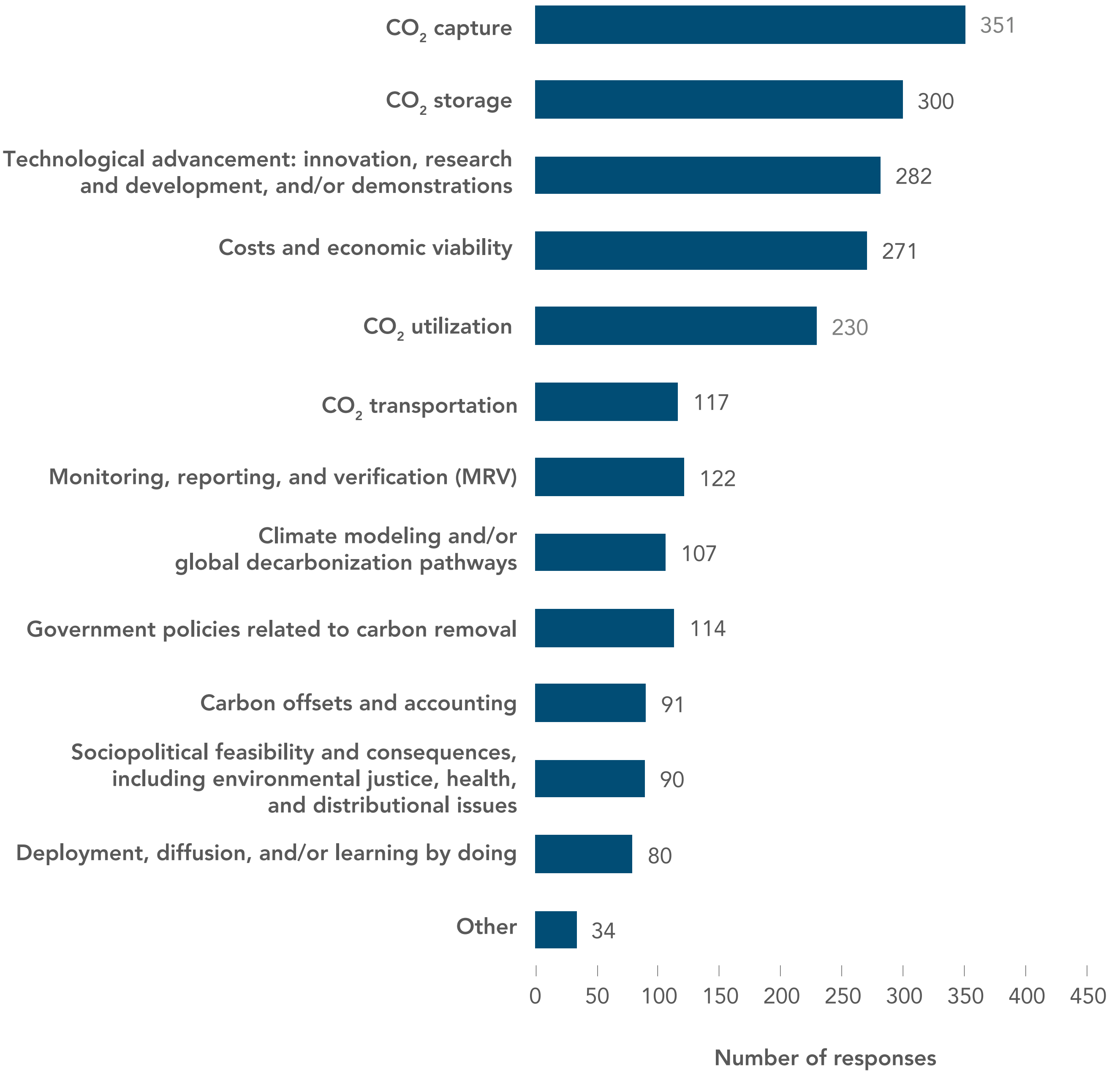


Our sample includes respondents with expertise in a range of CDR categories.[24] At least several dozen respondents have published or worked on each of the major approaches/technologies discussed in our survey, as shown above. Respondents also identified as having significant professional expertise on a range of relevant subtopics related to CDR. Many of those who selected "other carbon removal approaches/technologies" specified that they have expertise in CO_2 storage on the following question.

---

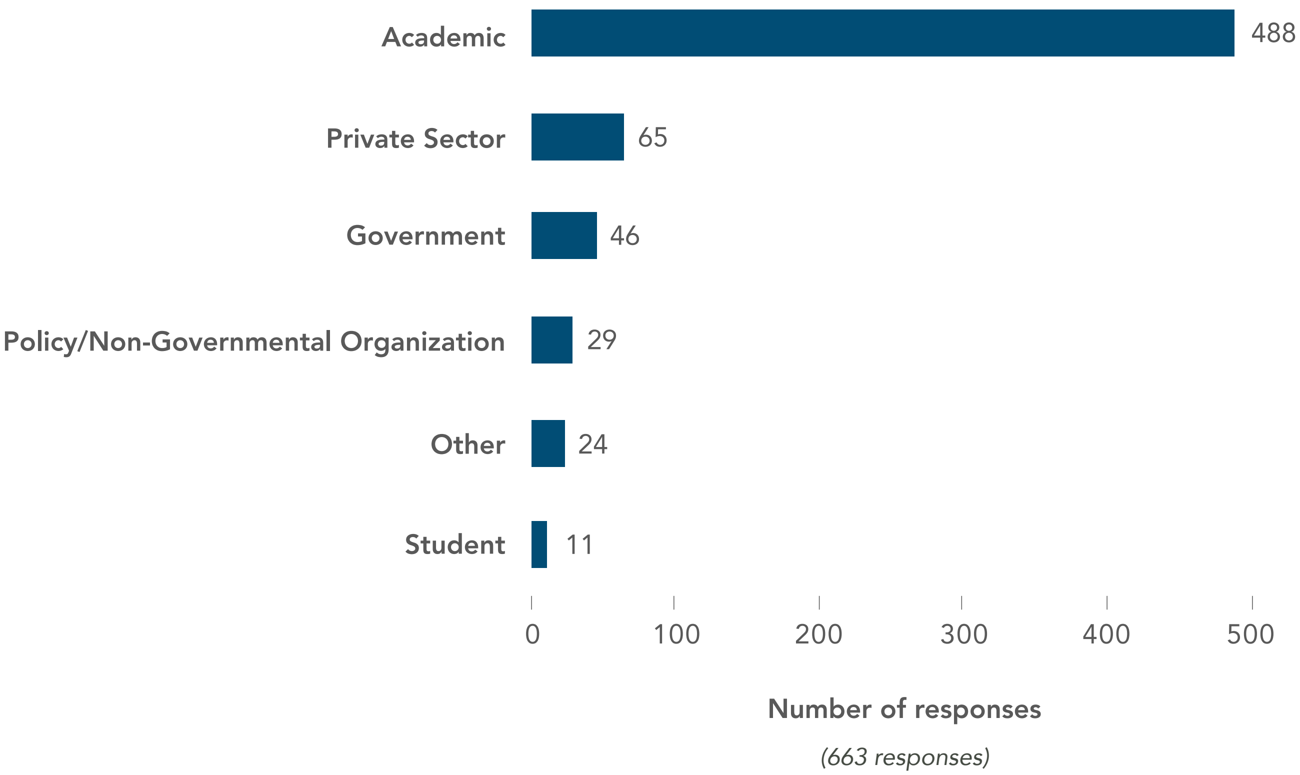
[24] Some respondents completed some or all of the initial background questions and then failed to complete substantive questions. We have omitted their responses here.

Topics on which respondents have published or developed significant professional expertise



(665 responses. Some respondents selected more than one choice)

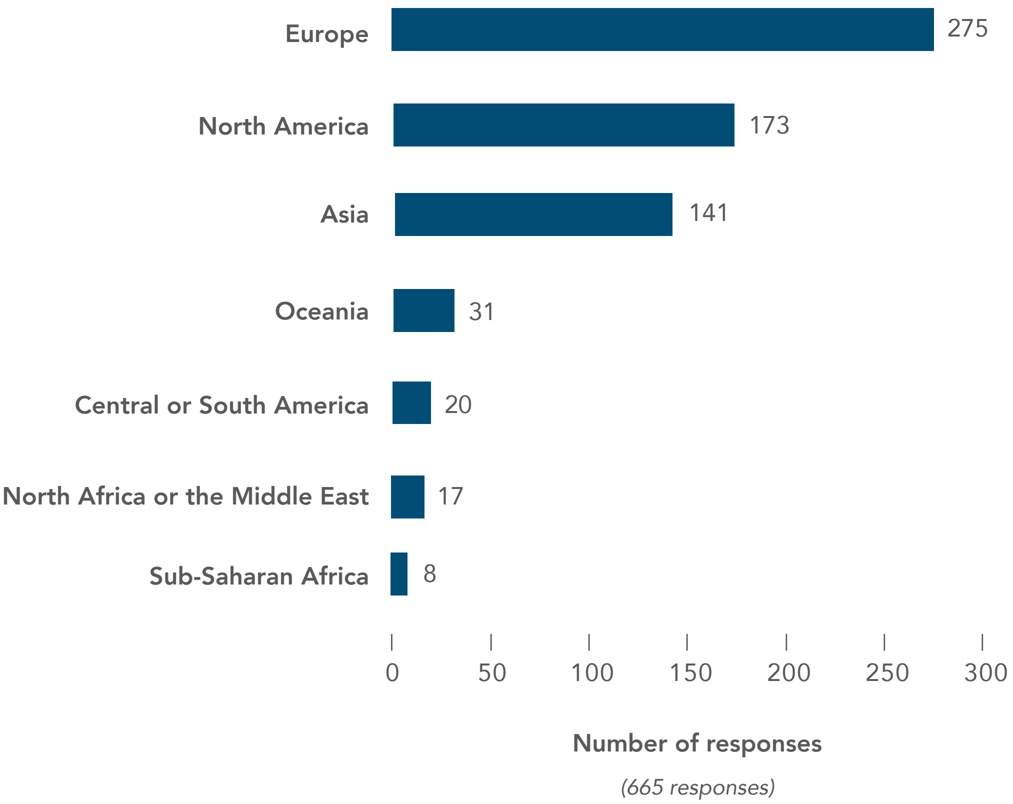
Respondents' primary professional positions, by category



The vast majority of respondents hold a primary position in academia, while several dozen others work in the private sector, government, and policy/non-governmental organizations. This breakdown is largely reflective of our selection criteria, which focused on experts who have published relevant articles in academic journals. While these journals do regularly publish research from authors working outside academia, most publications come from academics due to professional incentives and structural factors.

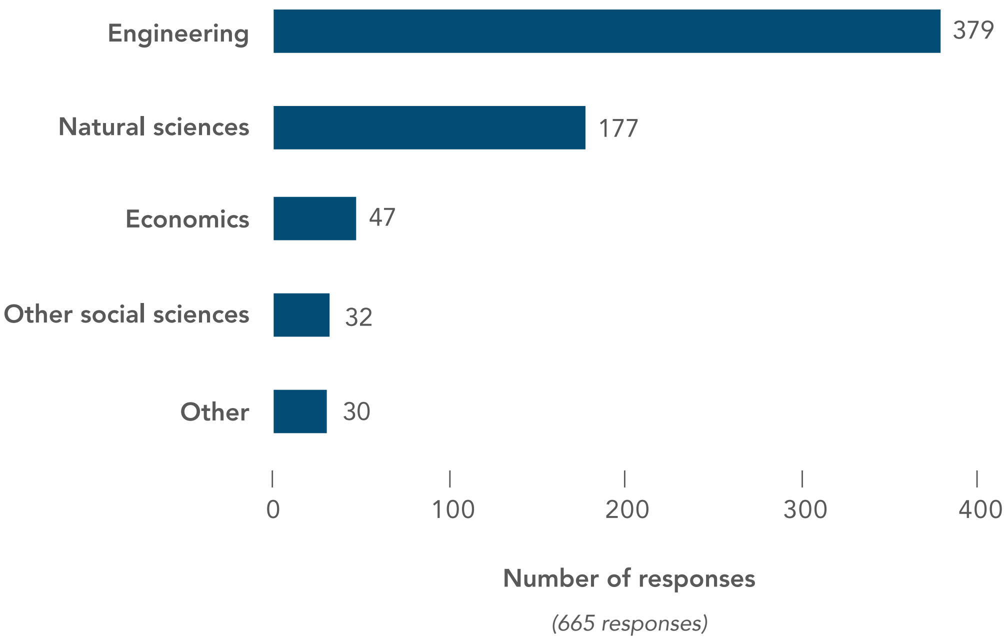
While the survey sample may underweight the views of experts in the private sector and some other categories, we felt that this selection methodology (and the corresponding weighting of academics) could produce a sample with less professional or financial bias toward particular CDR technologies or approaches. In theory, CDR experts who primarily work for a particular company may have a professional or financial incentive to express more favorability toward a particular CDR approach, whereas academics may be more likely to have more generally developed expertise and take a more neutral view.

Region where respondents are currently based



As shown above, the largest share of respondents is currently based in Europe, while significant portions are also based in North America and Asia. A smaller portion of respondents reside in Oceania, Central/South America, the Middle East, and Africa.

Discipline of respondents' highest professional degree



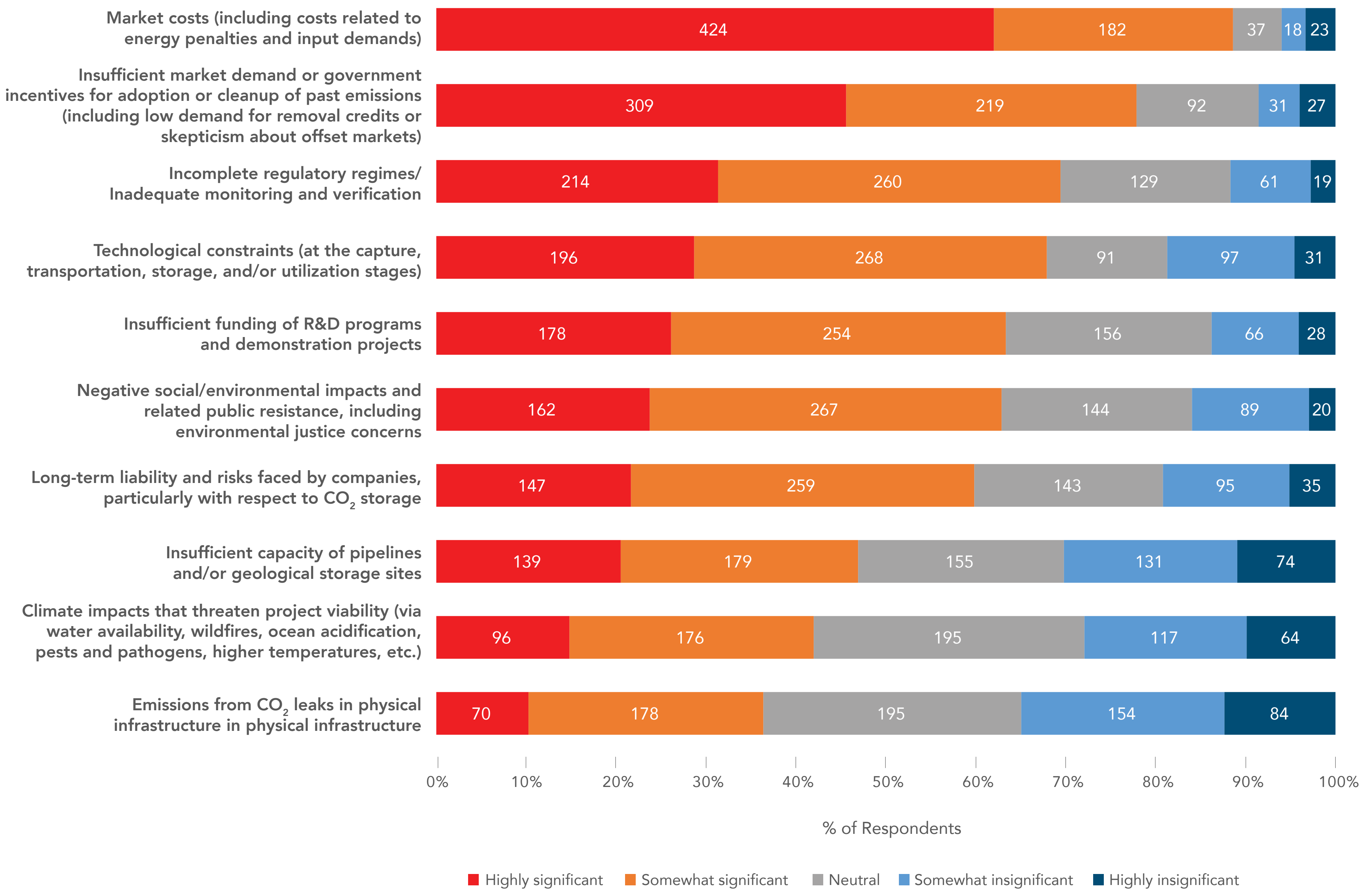
Engineers make up the largest portion of our sample, followed by respondents with degrees in the natural sciences. Just under 100 respondents have degrees in economics or other social sciences, and 36 others received their highest degree in another discipline. This mix suggests that our sample is relatively well qualified to weigh in on the technical and scientific factors underlying CDR. These factors play a large role in determining costs as well. Given the smaller share of social scientists, our sample may be less reflective of expert consensus on sociocultural factors.

Survey Results

The survey included 11 substantive questions, eight of which were quantitative forecasts. To ensure that respondents had access to relevant contextual information, we provided several explanatory notes and data points, and included links to definitions of key terms and other background information on all relevant survey pages. The full text of the survey is available in Appendix A.

The substantive portion of the survey began with two questions focusing on the most significant barriers to widespread CDR and the policies most likely to help make large-scale CDR viable and efficient. In addition to identifying expert consensus on barriers and possible solutions, these questions were designed to help address potential anchoring bias by highlighting a wide range of relevant factors that might affect the scale, cost, and growth rate of CDR in both positive and negative ways.

QUESTION 1



How significant of a barrier to widespread carbon removal is each of the following issues?

687 responses

Respondents identify numerous barriers to widespread carbon removal, though they rate market costs (including contributing factors, such as input demands and energy penalties[25]) as the most significant obstacle. The sample believes that the next most significant obstacle, by a relatively clear margin, is "insufficient market demand or government incentives for adoption or cleanup of past emissions (including low demand for removal credits or skepticism about offset markets)."

Based on the two top selections, there appears to be consensus that widespread CDR will be costly, and that market/government demand for these costly projects is likely to be a challenge. Many of our other survey questions focused on cost projections and related issues, shedding further light on the chief barriers identified by these experts.

The sample also widely agrees that other factors present significant barriers, including incomplete regulatory regimes; technological constraints; insufficient research and development (R&D) funding; and negative social/environmental impacts, including environmental justice concerns.

Clearly, experts believe that numerous barriers stand in the way of widespread CDR. Each of the 10 choices received more ratings of highly/somewhat significant than highly/somewhat insignificant, and only one choice was identified as significant by less than 40% of respondents ("Emissions from CO_2 leaks in physical infrastructure"). Nevertheless, a set of issues and a relatively clear order emerged, reflecting a level of consensus on the most problematic barriers to CDR. The findings from this question could help identify potential priorities for policymakers and others working to expand efficient and safe CDR deployment.

Notably, at least eight of the potential barriers identified in the question could theoretically be addressed, at least in part, through policy changes.[26] The next survey question focused on policies that might allow for increased CDR deployment.

In alignment with their focus on cost-related barriers in the previous question, respondents identify carbon pricing/government purchase of carbon removal as the policy most likely to help make large-scale carbon removal viable and efficient. The next two highest-rated choices are government-funded R&D and technology push/supply-side incentives, both of which could be expected to reduce market costs (and address technical challenges). Later in the survey, we asked questions about the impacts of these policy levers on CDR availability.

---

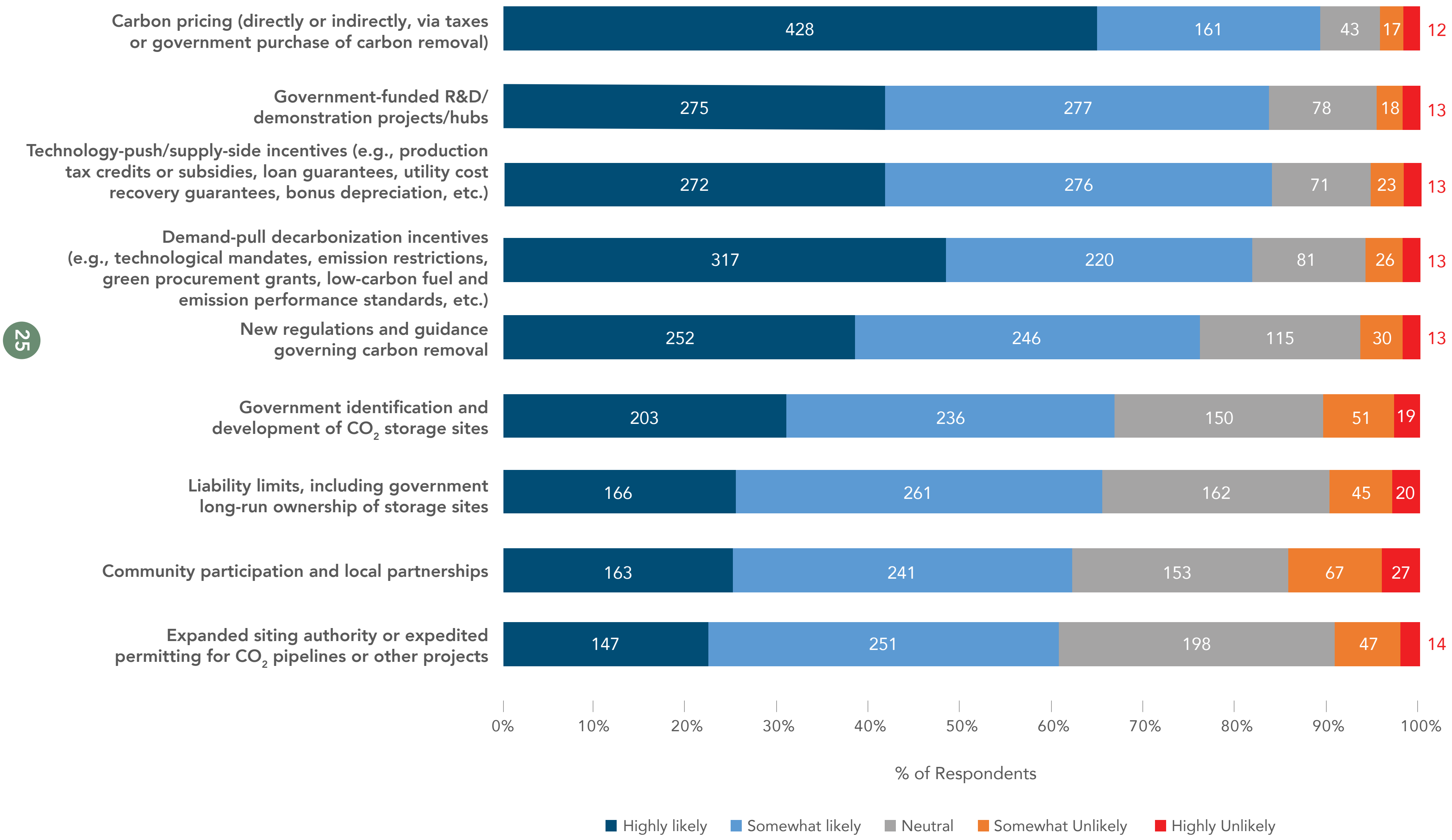
[25] "Energy penalties" refers to additional energy needs required to operate some forms of technological carbon capture equipment. This can increase operating costs or effectively reduce the energy output of, for example, a BECCS facility.

[26] Policy is unlikely to fully address one choice: "Climate impacts that threaten project viability (via water availability, wildfires, ocean acidification, pests and pathogens, higher temperatures, etc.)." Most respondents labeled this as a significant concern, though it received the second-lowest number of "significant" rankings. "Technological constraints…" could conceivably be addressed through R&D policy changes, though the survey did not solicit granular details about which constraints chiefly concerned the respondents or whether such constraints can be overcome.

QUESTION 2

Which policies, if implemented, are most likely to help make large-scale carbon removal viable and efficient?

664 responses



Respondents identify all of the options provided as likely to help enable growth in carbon removal: Each policy was rated as "likely" or "somewhat likely" by at least 60% of respondents, and none was rated "unlikely" or "somewhat unlikely" by more than 15%. In general, these results suggest that numerous policy changes in a wide range of areas will likely be needed to make large-scale carbon removal viable.

QUESTION 3

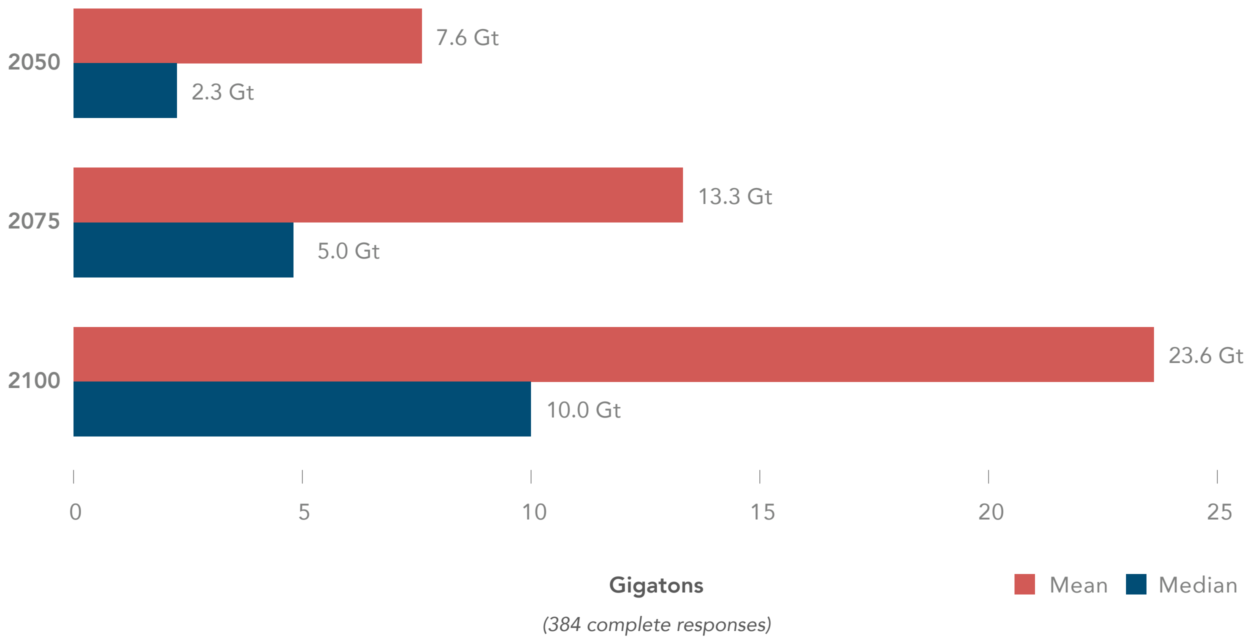
Our next question focused on the scale of CDR that respondents expect to occur in 2050, 2075, and 2100. Along with links to definitions of CDR methods, feasibility, and confidence intervals, the survey text for this question included the following reference points:

- Global energy-related CO_2 emissions in 2022: 36.8 Gt (36.8 billion tonnes)
- Annual CO_2 capture capacity of largest existing Direct Air Capture facility (Orca, in Iceland): 0.000004 Gt (4,000 tonnes)[27]

We included these reference points as relevant context to help inform respondents' quantitative forecasts. As discussed above, this and other forecast questions solicited respondents' 5th and 95th percentile estimates before their 50th percentile (most likely) value.

In each of the following years, how many gigatons of CO_2 do you think will be removed from the atmosphere (as a result of human intervention)?

50th percentile (most likely value)



---

[27] A larger facility, Mammoth, began operating in May 2024 (after the survey had closed).

Many respondents are particularly bullish about the growth and scale of CDR in the coming decades. The results discussed here exclude the highest and lowest 1% of estimates to eliminate outliers (we use this approach in our analysis of all open-ended forecast questions). Even after this trimming, the mean results for all years are significantly higher than the median results, reflecting some respondents' particularly large estimates.

Respondents predict multi-gigaton-scale CDR to occur by 2050, despite a dearth of current large-scale projects. However, the median projection is lower than the weighted estimates from Fuss et al., (2018), which project 6 Gt or more of total CDR activity in 2050 as feasible, based on a review of the literature and the authors' adjustments.

Looking farther into the future, our respondents predict a roughly linear growth rate of projects (based on removal amounts) between 2050 and 2100. This scale of CDR activity would likely require substantial infrastructure buildout and investment, and it would begin to approach the scope imagined in the net-zero scenarios of some prominent models. As mentioned above, the International Energy Agency predicts that 10.4 Gt of CDR will be needed annually by 2070 to reach net-zero emissions in the energy sector (IEA, 2020). While our respondents' median estimate of 5 Gt is well below this level, the mean estimate surpasses that projection.

However, these estimates are lower than the amount of CDR that these same respondents estimate will be needed to achieve global net-zero emissions in 2075 (based on responses to Question 8, discussed below). Even the 95th percentile projections of likely CDR amounts in 2075 are lower than respondents' 50th percentile estimate of the CDR amount necessary for reaching net-zero emissions in 2075. This finding indicates that respondents do not expect net-zero emissions to be achieved by 2075.

Our findings are roughly consistent with the estimates in Rennert et al. (2021)'s small-sample elicitation, despite analyzing different, but overlapping, categories of CO_2 emissions/removal. Specifically, for 2075, Rennert et al. find that the combined "annual net CO_2 emissions from natural carbon stocks and negative emissions technologies" are likely close to zero (implying that CDR efforts and natural sinks will roughly cancel out emissions from natural sources, such as wildfires). Our respondents estimate that CDR levels in 2075 will be sizable, though a direct comparison to Rennert et al. is not possible given that study's aggregation of CDR and positive/negative land-based emissions. Notably, both our study and Rennert et al. find a significant increase in CDR between 2050 and 2100.

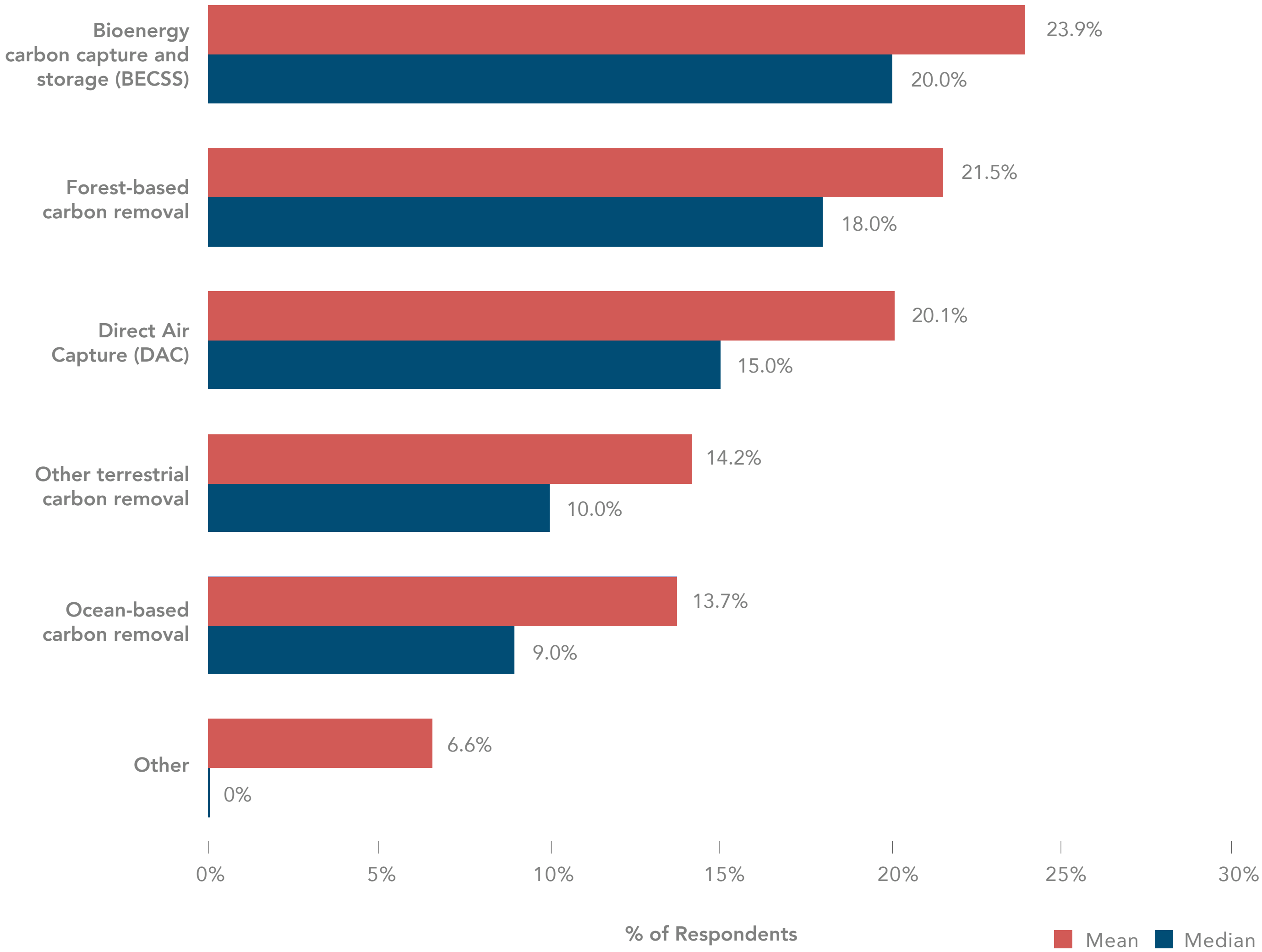
QUESTION 4

Building on respondents' estimates of the scope of CDR in 2075 from Question 3, we asked them to break down this aggregate amount by capture method and storage/utilization method in Questions 4 and 5, respectively. Specifically, we asked respondents to disaggregate their 50th percentile/most-likely estimate for 2075. Respondents expect a wide range of approaches to be used for capture and storage/utilization.

Estimated percentage of total CDR activity by category in 2075

(based on respondents' most-likely CDR scenarios)

528 responses, 97 answered "No Opinion"



Respondents predict that BECCS will provide the largest share of CDR in 2075, followed by forest-based CDR. This projection aligns with much of the CDR literature—many integrated assessment models project that BECCS will be the primary negative-emissions approach used during this century, and IEA (2022) identifies forest-based approaches and BECCS as some of the most-promising CDR options.[28] However, many analysts predict that these approaches will be limited by competing land-use and food-security demands sometime later this century (those concerns may have kept respondents from offering even higher estimates). The respondents estimate that DAC will also provide roughly 15-20% of total CDR in 2075, suggesting that they do not expect technological and cost concerns to limit DAC's ability to develop into a large-scale CDR option. Terrestrial and ocean-based CDR efforts are also projected to play smaller but significant roles in 2075 CDR efforts.

To facilitate further comparison, we use responses to Questions 3 and 4 to calculate the estimated removal amounts for each CDR approach in 2075 (by multiplying respondents' estimates for total gigatons removed in 2075 by their estimated percentages for each by CDR category); see Table 3.[29] For the most part, these estimates fall within the ranges of estimated feasibility for each CDR approach as identified by Fuss et al. (2018), though their ranges focus on 2050 while our estimates focus on 2075.

TABLE 3.

Estimated CO_2 Removed by CDR Approach in 2075

(based on respondents' most-likely removal amounts and breakdowns by approach)

CDR Approach	Gt/CO_2 Removed in 2075
BECCS	2.7
Forest-based	2.4
DAC	2.3
Other terrestrial	1.6
Ocean-based	1.5
Other	0.7

528 responses. Estimates reflect the product of full sample mean responses to Questions 3 and 4.

---

[28] Specifically, IEA (2022) finds that "Together with DACS, the most promising CDR options include afforestation and reforestation (AR) and bioenergy with CCS (BECCS)."

[29] We make this calculation using two approaches: (1) we multiply the mean of the responses for the most likely amount of removal in 2075 from Question 3 and the mean response for the estimated percentage contribution by CDR category in 2075 from Question 4; (2) we multiply each individual's response to Question 3 and their response to Question 4 and then calculate the mean. Results from the second approach can be found in Appendix C.

Critically, the DAC value is well below the upper limit identified by Fuss et al. (2018) of 5 Gt/year for 2050. It is also far below the 40 Gt/year limit selected by IPCC (2022), which assumes that existing constraints, such as storage limits, will be addressed. Our respondents may either view some DAC constraints as more significant hurdles, or predict that government policies will not create sufficient demand for CDR approaches overall (respondents identify this as a major concern in Question 1, and offer relatively modest removal estimates for 2050 compared to some studies).

Respondents project that roughly 1.5 Gt of CO_2 will be removed by ocean-based CDR methods in 2075; this is also roughly consistent with the conclusions of Fuss et al. (2018). Specifically, Fuss et al. (2018) do not provide a scale estimate for ocean fertilization given their projection of its low feasibility, but they project 2 to 4 Gt/year of removal from enhanced weathering, some of which would be expected to occur in coastal areas (we instructed our respondents to consider coastal enhanced weathering as an ocean-based CDR approach, along with biological approaches like seaweed/algae cultivation; blue carbon management; and chemical approaches like alkalinity enhancement). Our results imply that ocean-based removal activities may be on the lower end of estimated feasibility ranges. The IPCC (2022) provides an extremely wide potential range of 1 to 100 Gt/year for ocean fertilization.

Our respondents predict that "other terrestrial" approaches will provide 1.6 Gt of removal in 2075, much less than the feasible range estimated by Fuss et al. (2018), who project that biochar and soil carbon sequestration alone have the ability to provide 2.5 Gt/year to 7 Gt/year in 2050. Our respondents may expect there to be more significant practical, sociopolitical, or economic constraints on this set of CDR approaches. Again, an alternative explanation is insufficient demand for CDR overall, as is consistent with the discussion above for Question 1 (barriers to CDR) and Question 3 (the most-likely quantity of removal).

As another point of comparison, the Sovacool et al. (2022) survey findings estimated the following median 2050 removal amounts by approach: afforestation and reforestation (2 Gt), soil carbon sequestration (2 Gt), ecosystem restoration (1 Gt), blue carbon and seagrass (0.35 Gt), biochar (0.75 Gt), BECCS (2 Gt), enhanced weathering (0.75 Gt), ocean alkalinization or fertilization (0 Gt), DAC (1 Gt), and CCUS (1 Gt). Our results are relatively consistent, though slightly less conservative, than their median responses (though their mean estimates are dramatically higher than our respondents' projections, with 2050 removal amounts that vastly exceed total global emissions).[30]

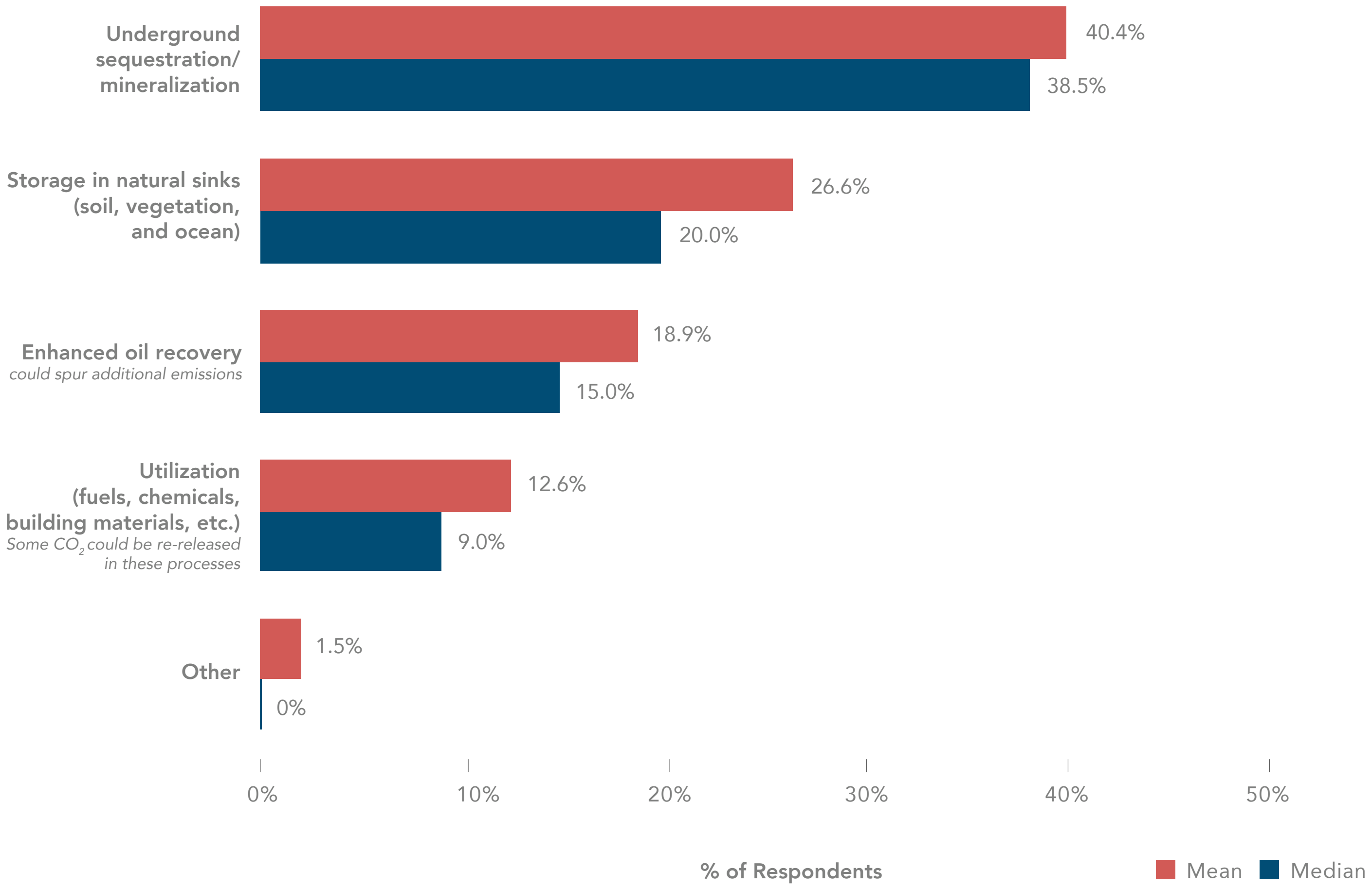
---

[30] The mean estimates from Sovacool et al. (2022) are reproduced in our Recent Relevant Studies section.

QUESTION 5

What percentage of CO_2 removed/captured do you think will be stored or used in the following ways in 2075?

528 respondents, 92 answered "No Opinion"



We next asked respondents to estimate how the removed/captured CO_2 in their earlier answer will likely be stored or used. Again, respondents predict a mix of approaches. While underground storage/mineralization represents a plurality (roughly 40%), it is projected to provide less than half of the total amount, with natural sinks, enhanced oil recovery, and utilization jointly playing a larger role.

Given the lack of follow-up questions, it is unclear why respondents estimate that natural sinks (forests, other terrestrial, and ocean-based carbon removal) will account for 37-49% of estimated capture, but only 27-39% of storage.[31] One potential explanation is that respondents accounted for leakage and potential lack of durability from carbon sinks, land-use changes, and

---

[31] The upper boundary of this range assumes that 100% of utilization is the storage of carbon in timber and other resource production.

utilization. Many forestry and land-use offset projects have been plagued by integrity issues and questions about permanence. And as noted in this survey question, utilization (fuels, chemicals, building materials, etc.) can result in the re-release of some CO_2. Question 1 of the survey also highlighted that climate impacts may threaten some CDR projects (via water availability, wildfires, ocean acidification, pests and pathogens, higher temperatures, etc.). Given that a plurality of respondents rate this a significant or very significant problem, such concerns could be affecting these estimates. In particular, given the high share of forest-based CDR that experts estimate in Question 4, the threat of wildfires could be a significant factor.[32] The existing literature also highlights leakage concerns for soil sequestration and ocean fertilization (Fuss et al., 2018).

Respondents also estimate a significant level of enhanced oil recovery, which, as the survey noted, could spur additional emissions. This EOR estimate is consistent with respondents' belief that net-zero-emissions targets are unlikely to be achieved (see the discussion of results from Questions 8 and 9).

QUESTION 6

In the initial portion of Question 6, we asked respondents to select the carbon removal approach/technology over which they have the most expertise. We then asked them to estimate the average (mean) cost of carbon removal ($ per tonne of CO_2) in 2075 for their selected approach, as well as the average cost of all other technologies/approaches (grouped together). We provided the following additional guidance:

> *Please factor in all market costs, including annualized capital costs, operational/management costs, and energy penalties, of all the relevant steps: capture, transportation, storage, and utilization. Please consider technological and sociopolitical constraints, leakage, and climate system dynamics. Do not account for inflation when answering the question – please use current (2023) dollars.*

As in other forecast questions, we asked respondents to fill out their 5th and 95th percentile estimates before providing their 50th percentile (most-likely value), and carefully assess whether the full range of possible events fall within or outside this confidence interval.

---

[32] Another possible explanation is a cognitive bias (potentially from the lack of a direct mention of forests in Question 5) or simple mental errors in reporting. Future work will analyze whether these inconsistencies hold across the entire sample or just for a few individuals.

For the technology/approach over which you have the most expertise, what do you think will be the average (mean) cost of carbon removal in 2075?

50th percentile/most-likely estimates

($ per tonne of CO_2)

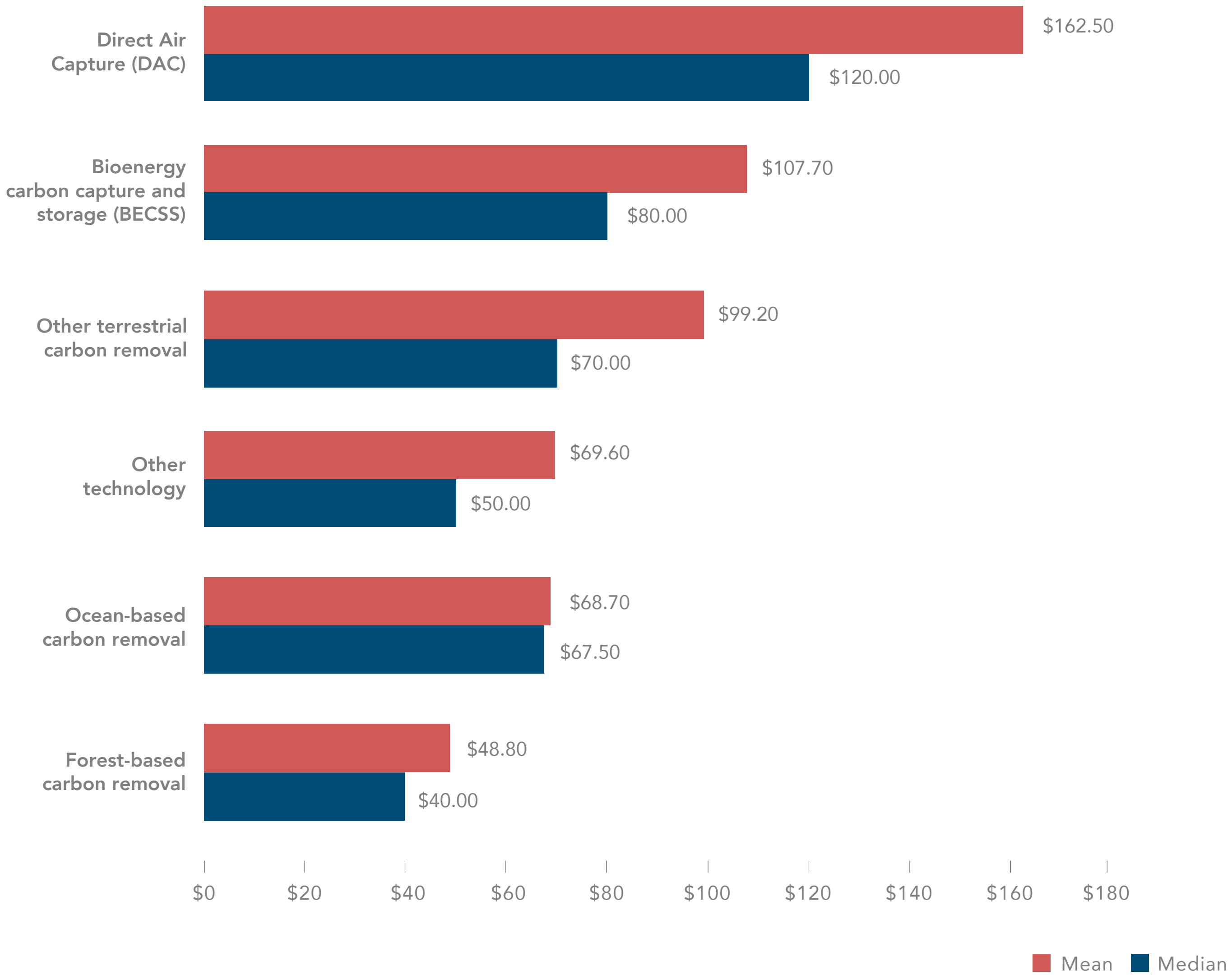


TABLE 4.

Average (Mean) Cost of CDR in 2075 by Approach/Respondent Area of Expertise

($ per tonne of CO_2)

In Question 6, each respondent was asked to estimate the cost of the approach over which they have the most expertise, as well as the average cost of all other approaches

	Mean cost estimate	Median cost estimate	5th percentile estimate	95th percentile estimate	Observations
Direct air capture (DAC) – projected by DAC experts	162.5	120	40	500	72
Avg. cost of all other CDR approaches (DAC experts)	133.2	100	20	400	62
Bioenergy carbon capture and storage (BECCS) – projected by BECCS experts	107.7	80	20	210	101
Avg. cost of all other CDR approaches (BECCS experts)	184.6	135	20	500	94
Other terrestrial carbon removal – projected by terrestrial experts	99.2	70	20	500	35
Avg. cost of all other CDR approaches (Terrestrial experts)	163.2	100	16	280	34
Other CDR approaches – projected by experts on other approaches	69.6	50	5	200	53
Avg. cost of all other CDR approaches (Experts on other approaches)	127.4	100	10	500	49
Ocean-based carbon removal – projected by Ocean experts	68.7	67.5	12	150	10
Avg. cost of all other CDR approaches (Ocean experts)	92.2	55	17	300	10
Forest-based carbon removal – projected by Forest experts	48.8	40	15	120	21
Avg. cost of all other CDR approaches (Forest experts)	112.0	100	23	275	20

One key finding from this question is that respondents predict lower market costs for the enhancement of natural sinks (i.e., nature-based approaches) compared to technological approaches (i.e., BECCS and DAC). Forest-based carbon removal is estimated to be the cheapest of all CDR approaches, with a mean cost of $49/tonne. This projection is consistent with respondents' large estimated market share for forest-based CDR. The other nature-based approaches are estimated to have higher average costs and lower market shares. Similarly, of the technological approaches, BECCS is projected to be significantly cheaper than DAC at a mean cost of $108/tonne compared to $163/tonne, consistent with its larger market share. DAC is the only approach with an estimated mean cost that exceeds the estimated mean cost of all CDR approaches in aggregate.

It is noteworthy that respondents' cost estimates for all CDR approaches, including DAC, are significantly lower than prominent estimates for the social cost of carbon. The U.S. Environmental Protection Agency's central estimate (of the economic damage caused by a marginal tonne of CO_2 emitted in 2024) is $210/tonne (2020 USD), and this figure will be dramatically larger in 2075, at $391/tonne (2020 USD) (EPA, 2023). This suggests that respondents expect all of the CDR approaches discussed in this survey to be cost-benefit justified, at least by 2075.

Respondents who have studied a particular CDR approach almost uniformly predict that their known approach can be carried out more cheaply than competing options. We asked respondents to estimate both the average cost of the technology over which they have the most expertise, and the average cost of all other CDR approaches (grouped together). We found that all subgroups except DAC experts projected the "all other approaches" category to be more expensive than the approach they have studied. One possible interpretation of this finding is that experts with particularized knowledge believe that perceived cost barriers for the CDR approach they know best—across nearly all approaches—can be overcome in the coming decades. Respondents do not express this same level of optimism for CDR approaches over which they have less expertise.

Analyzing these cost projections alongside respondents' CDR market-share estimates yields additional nuance. Despite their relatively higher estimated average costs, respondents predicted that BECCS and DAC will have larger market shares than most of the cheaper nature-based approaches. One possible explanation is that marginal costs (rather than average costs) determine the market price and quantity in a competitive market. DAC and BECCS may have high relative fixed costs and lower (and likely declining) marginal costs, such that these industries can take advantage of economies of scale and claim larger market shares. In contrast, the natural approaches may face lower marginal costs that rapidly increase with expansion, potentially due to land constraints, saturation limits, and heterogeneity of potential locations for nature-based CDR approaches. Another explanation may be respondents' expectations about government support/subsidies and additional revenue sources.[33] Despite higher costs for certain approaches, respondents may expect significant subsidies (such as those included in the U.S. Inflation Reduction Act), which may influence the overall mix of CDR approaches. Finally, some CDR methods produce additional revenue streams, such as energy production from BECCS. In such cases, respondents may separate these project benefits from costs, leading to an overestimation of the net cost of adopting the technology.

---

[33] For example, the European Union and the United Kingdom strongly support the use of biomass burning to achieve net-zero emissions, including through the use of subsidies (Booth and Blackshaw-Crosby, 2023; Mehta, 2023).

Average Costs and Total Costs of CDR in 2075

Using responses to Questions 3 through 6, we are able to calculate the average cost and total cost of CDR in 2075 on the likely emissions path.[34] We find that the mean and median average cost of all CDR activities is $127/tonne and $98/tonne, respectively, with a 90th percent confidence interval of $24/tonne to $300/tonne. The mean and median total costs are $749 billion and $180 billion, respectively, with a 90th percent confidence interval of $2 billion to $4.25 trillion. Critically, these costs are conditional on the individual's forecast of the most-likely emissions path, such that we would expect the average cost to decline with CDR magnitude, as individuals with lower cost expectations should expect higher CDR uptake.

TABLE 5.

Average and Total Cost of All CDR Activities in 2075

Based on Respondents' Estimates for Questions 3-6

Cost Type	Mean	Standard Deviation	5th Percentile	50th Percentile	95th Percentile	Sample Size
Average Cost	**$127/tonne**	135.7	$24/tonne	$98/tonne	$300/tonne	261
Total Cost	**$748.7 billion**	1660.7	$1.8 billion	$180 billion	$4.25 trillion	235

QUESTION 7

Our next question focused on the effect of CDR on other emissions-reduction efforts. Many policymakers and advocates have voiced concerns about potential moral hazard due to overreliance on CDR as an offset strategy. We asked respondents to consider a scenario where no large-scale CDR efforts become viable by 2075, and select whether they thought other emissions-mitigation efforts would be "roughly identical," "significantly greater," or "significantly smaller" due to the unavailability of carbon removal as an offset strategy.

---

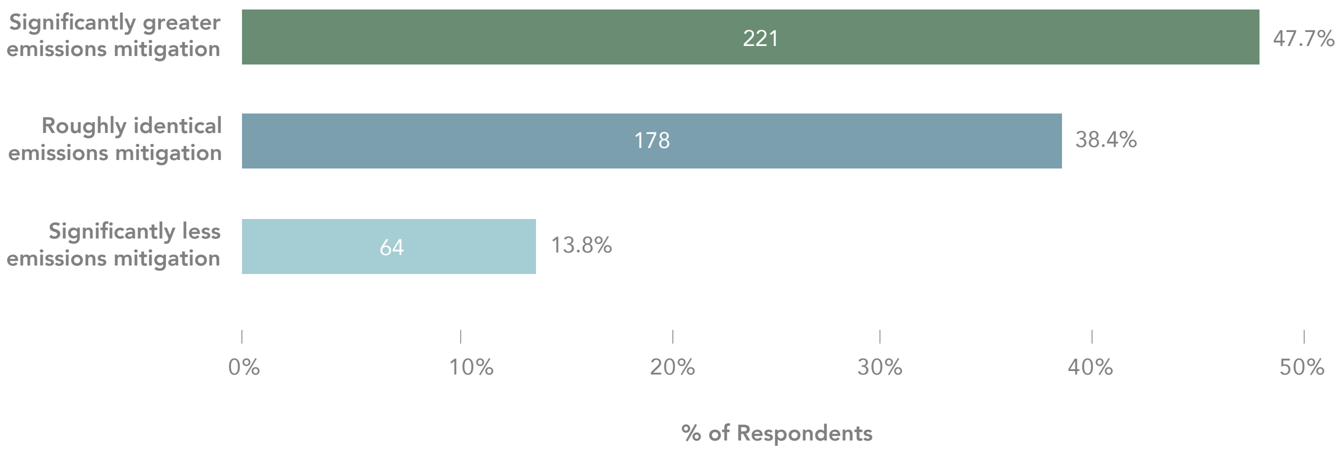
[34] From Question 3, we have respondents' most likely amount of CDR in 2075 (E). From Question 4, we have the proportion of total CDR in 2075 (P_i) attributed to each approach (i). From Question 6, we know the average cost (AC_i) for the approach over which the respondent is most familiar ($i=j$) and all other approaches ($i=k$). The average cost equals

$$AC = \frac{(AC_i \times (P_j \times E) + AC_k \times ([1 - P_j] \times E)}{E} = P_j AC_i + (1 - P_j)\, AC_k$$

Therefore, total cost (TC) is $TC = AC \times E$.

Under a scenario where no large-scale carbon removal approaches become viable by 2075, how do you think other global emissions-mitigation efforts would be affected?

463 responses. Values within bars provide number of responses.

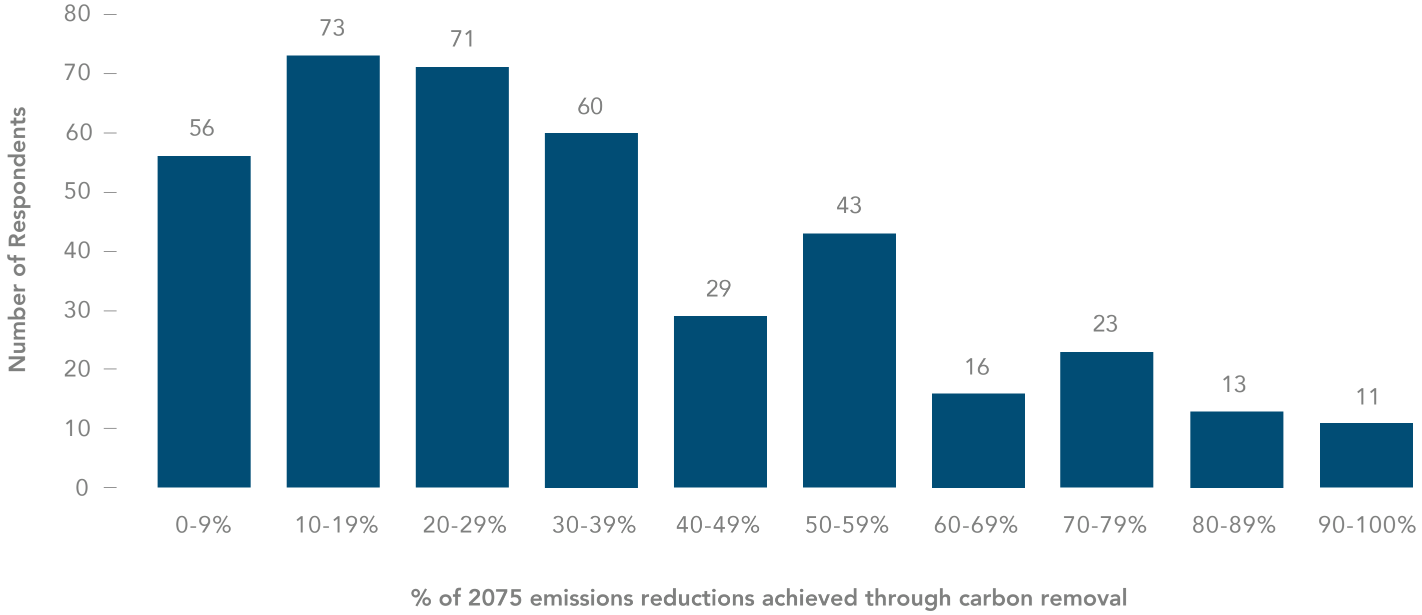


Nearly 48% of respondents believe that emissions-mitigation efforts would be significantly greater if CDR is found to be unviable. This finding suggests a belief that society has the capacity to expand decarbonization efforts, and that the promise of CDR offsets is either a moral hazard limiting some emissions reductions or a lower-cost pathway that could make some less-desirable mitigation efforts unnecessary. More than 38% of respondents believe that other mitigation efforts would be unaffected by the unavailability of CDR, suggesting that this group does not see moral hazard issues as a looming concern. Roughly 14% of respondents believe that the unavailability of CDR would significantly reduce other emissions-mitigation efforts, potentially because climate goals could be seen as unachievable under such a scenario, or because other options such as geoengineering could be prioritized.

QUESTION 8

Question 8 focused on the scope of CDR under a global net-zero emissions scenario, using the following question and supporting information:

> Models suggest that achieving global net-zero emissions in 2075 would entail mitigation of roughly 123 gigatons of CO_2 in 2075 (the difference between a business-as-usual emissions projection and a net-zero emissions projection).*
>
> **Under this 2075 net-zero GHG scenario, what percentage (of the 123 Gt mitigated) do you think would be achieved through carbon removal?**
>
> Please consider technical, sociopolitical, and economic constraints.
>
> **Based on the IPCC's emission scenario definitions, achieving net-zero emissions in 2075 is consistent with a C3 or C4 (net-zero) emissions path relative to a C8 (business-as-usual) emissions path; this would entail global mitigation of roughly 123 gigatons of CO_2 in 2075.*



Under this 2075 net-zero GHG scenario, what percentage (of the 123 Gt mitigated) do you think would be achieved through carbon removal?

395 responses analyzed here (an additional 86 respondents selected "I can not answer this question" and provided no numerical answer)

Note: models suggest that achieving global net-zero emmisions in 2075 would entail mitigation of roughly 123 gigatons of CO_2 in 2075 (the difference between a buisness-as-usual emissions projection and a net-zero emmisions projection).

The vast majority of respondents predict that enormous levels of CDR will be needed under this 2075 net-zero scenario. More than 85% of respondents believe that more than 12 Gt of CDR would be needed, with some estimating a need for dozens or even 100+ Gt. The mean estimate is that 28.7% of total emissions reductions would need to come from CDR, and the median estimates is 20%. (Presumably, remaining reductions would be achieved through traditional emissions avoidance/reduction strategies.)

As mentioned above, responses to this question and Question 3 (on the most likely scale of CDR in 2050, 2075, and 2100) can be analyzed together, providing additional context. Respondents' 95th percentile projections of CDR amounts in 2075 are still lower than the 50th percentile estimates for this question, indicating that respondents do not believe such high levels of CDR are realistic, and that they do not expect net-zero emissions to be achieved by 2075.[35]

---

[35] Comparing individual responses to Questions 3 and 8, we also find that over 95% of respondents (out of 344) think that a a net-zero target is unlikely to be met by 2075.

QUESTION 9

Question 9 explored the impact of R&D funding on the timeline for widespread CDR. The prior question prompted respondents to estimate the role of CDR in a net-zero emissions scenario; a large majority of respondents provide very large estimates for the CDR levels needed. Question 9 then presented this question and context:

> When are net-negative annual CO_2 emissions likely to be feasible on a global scale, given technological and social constraints? Please specify when mitigation rates could reach more than 100% of global annual emissions under two scenarios:
>
> > (1) Aggressive global climate policy equivalent to a global carbon tax of $750/tonne (in 2023 USD) beginning in 2025 and rising annually. Current R&D funding policies remain unchanged;
> >
> > (2) The same aggressive climate action in Scenario 1, but governments also commit to ambitious R&D funding for zero-emissions technologies and carbon removal equivalent to 10% of global GDP annually, beginning in 2025.

Context:

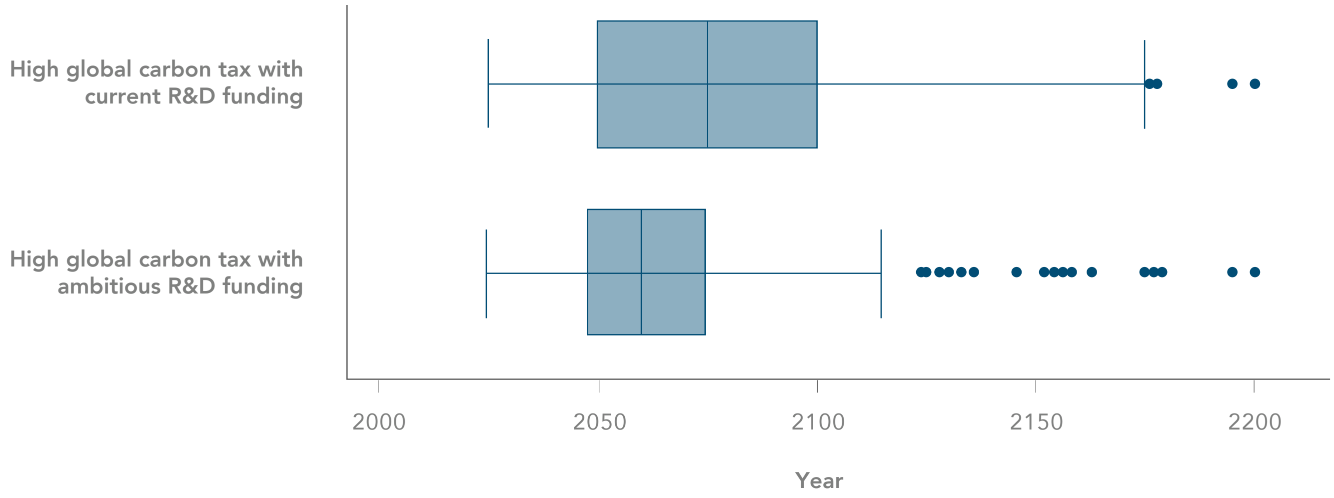
- Based on policies and corporate spending on emissions mitigation before the U.S. passage of the Inflation Reduction Act, DICE-2016R2 calculates an implicit price of CO_2 of $3/tonne for emissions in 2025 (in 2021 USD).
- In 2022, IEA member countries (most of continental Europe, North America, Australia, Japan, New Zealand, South Korea, and Turkey) cumulatively spent $28 billion (2022 USD) on publicly funded R&D for low-carbon energy projects (energy efficiency, carbon capture and storage, renewable energy, nuclear, hydrogen/fuel cells, energy storage, and other cross-cutting technologies and research).
- The United States' energy and industrial sectors invested $151 million in 2022 (2022 USD) in carbon capture technology, according to the Clean Investment Monitor Project.
- According to the IEA, the future capacity of carbon capture projects announced in 2022 was 75.5 to 81.1 Mt CO_2/yr worldwide. In comparison, global operational capacity of carbon capture was approximately 45 Mt CO_2/yr in 2022.

The question also included a link to our definitions of technological and social/political feasibility.[36]

---

[36] Our definitions for these techno-economic terms can be found at: https://policyintegrity.org/documents/Techno-Economic_Terms.pdf

When are net-negative annual CO_2 emissions likely to be feasible on a global scale, given technological and social constraints?



336 responses analyzed here (an additional 107 respondents said they could not answer this question because they believe 100% mitigation is not feasible on this timeline)

The blue boxes show the 25th and 75th percentiles of respondents' answers, and the median is reflected by the central vertical line in the box. The whiskers represent the lower and upper adjacent point lines.[37] *The dots are outlier values.*

Respondents believe that ambitious R&D funding can play a major role in accelerating the deployment timeline for technologies such as CDR. In the scenario where this R&D funding is added to an already historically aggressive carbon-pricing (or equivalent) policy, respondents estimate that net-negative global emissions would become feasible significantly earlier—potentially before 2050. They also project that the uncertainty and range of feasibile timeframes would shrink considerably. These findings are consistent with literature on R&D and climate-related market failures, which suggests that policymakers must separately address both (1) pollution-externality market failures and (2) R&D underinvestment market failures, since no single policy instrument is likely to address them simultaneously.[38]

In Question 2, respondents selected (direct or indirect) carbon pricing and R&D-related efforts as the two most promising policies to make CDR viable and efficient. Clearly they believe that the combination of these two policies would be vastly more effective than a single aggressive policy.

---

[37] These values are 1.5 times the difference between the 25th and 75th percentiles, added to the 75th and subtracted from the 25th percentiles.

[38] Policymakers must address two market failures in the climate change context: a negative pollution externality leading to excessive GHG pollution, and an underinvestment in R&D for zero and negative-emission technologies because parties do not expect to capture the full value of R&D investments, including from learning-by-doing. As the two market failures cannot be addressed by one policy mechanism alone, policymakers should introduce an additional market mechanism to compliment a greenhouse gas tax. Traditionally, an R&D investment subsidy is the preferred policy to address a positive innovation externality, whereby society benefits from an economic actor's investment in innovation through information spillovers and dispersion that the investor is unable to capitalize (Goulder and Schneider,1999; Aldy et al., 2010; Gillingham and Sweeney, 2010).

The results from this question suggest that ambitious R&D funding may be a particularly powerful tool, and that assumed constraints around widespread CDR deployment may be malleable.

QUESTION 10

Forecasts of costs are critical to understanding the potential future of negative-emissions approaches. As noted by respondents to Question 1, market costs of CDR approaches are likely to be the primary barrier to widespread deployment.

In Question 6, we focused on the average costs of CDR on the most-likely emissions path. However, as noted above, the most-likely emissions path identified by our respondents is insufficient to reach net-zero emissions during this century, such that it is incompatible with UN climate targets. Moreover, the average cost tells us little about market prices, which are determined when marginal cost equals marginal revenue.

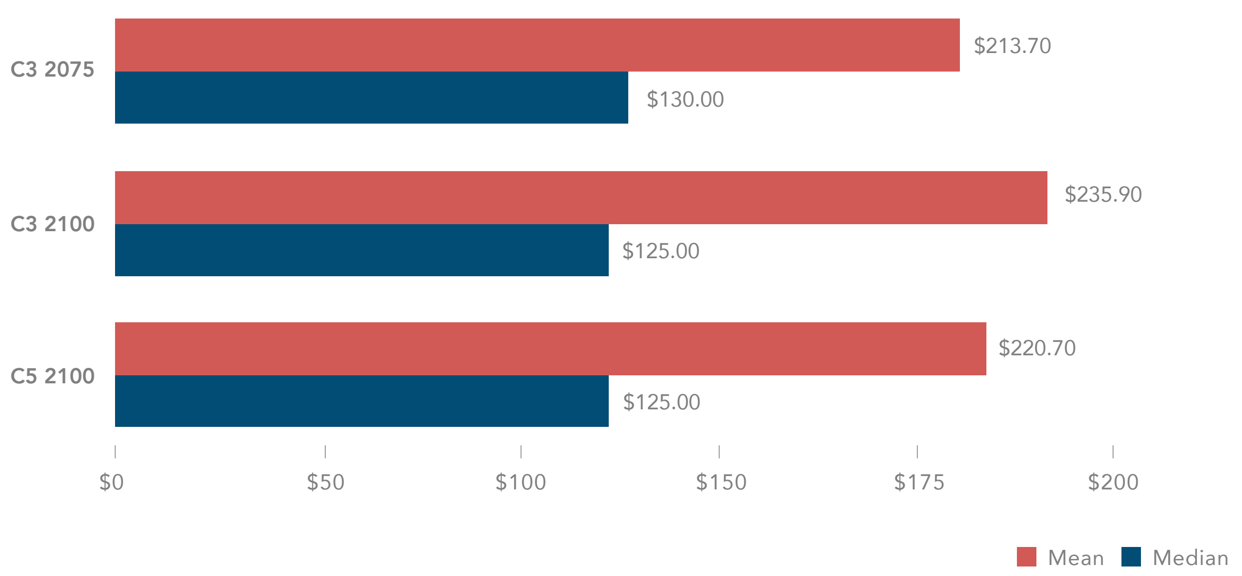
To improve our understanding of the expected price of CDR if UN climate goals are met, we elicited the marginal cost of abating an additional tonne of emissions under three scenarios, drawn from the IPCC's latest classification of climate scenarios.[39]

Scenario	Reference	Time Passes	Climate Scenario Change
IPCC Climate Scenario & Year	Climate Scenario C3 2075	Climate Scenario C3 2100	Climate Scenario C5 2100
Abatement level (% of emissions controlled) relative to RCP8.5 pathway (C8 Scenario)	101% (-126 Gt with at least -1 GT of carbon removal)	107% (-134 Gt with at least -8 GT of carbon removal)	101% (-126 Gt with at least -1 GT of carbon removal)

The C3 scenario assumes net-negative emissions in 2075 and thereafter to keep global average surface temperature below a 2°C increase, relative to pre-industrial levels, without overshoot (i.e., without allowing global average surface temperatures to temporarily exceed the 2°C limit before CDR lowers emissions and temperature to meet the target). In contrast, the C5 scenario assumes net-negative emissions in 2100 and thereafter to keep temperatures below 2.5°C at a lower cost (IPCC, 2022). The exact scenarios were selected such that the amount of mitigation, including negative emissions, were the same for the C3 Scenario in 2075 and the C5 Scenario in 2100. Mitigation efforts are measured relative to a SSP5-8.5 baseline (IPCC, 2022). We asked experts to provide their 5th, 50th, and 95th percentile estimates of the marginal cost/price of carbon removal for each of the three scenarios.

---

[39] The IPCC climate scenario system breaks down potential emissions levels into eight groups; see Appendix D. Using this classification system and scenario data from AR6, we developed two scenarios consistent with C3 and C5 scenarios as specified by the IPCC.



What is the marginal cost/price of carbon removal for the three scenarios below?

50th percentile (most likely value)

TABLE 6.

Responses to Question 10

Scenario	Year	Percentile	Observations	Mean Estimate	Standard Deviation	5th Percentile Estimate	50th Percentile Estimate	95th Percentile Estimate
C3	2075	5	93	$120	$159	$10	$70	$500
C3	**2075**	**50**	**93**	**$214**	**$238**	**$20**	**$130**	**$750**
C3	2075	95	93	$370	$355	$20	$250	$1,000
C3	2100	5	91	$134	$191	$5	$60	$500
C3	**2100**	**50**	**91**	**$236**	**$329**	**$12**	**$125**	**$800**
C3	2100	95	91	$437	$675	$20	$200	$1,500
C5	2100	5	88	$133	$193	$5	$73	$500
C5	**2100**	**50**	**89**	**$221**	**$285**	**$12**	**$125**	**$750**
C5	2100	95	88	$395	$472	$20	$250	$1,300

The resulting marginal cost estimates shown in Table 6 are below the central estimates for the social cost of carbon from EPA (2023) of $391 (2020 USD) in 2075, indicating that respondents expect the climate benefits of negative emissions to exceed the costs. Focusing on the 50th percentile/most-likely estimates, respondents project a mean marginal cost of $214/tonne to $236/tonne, while the range of median estimates is significantly lower at $125/tonne to $130/tonne. The median estimates are generally consistent with assumptions about the impact of innovation, as the median marginal cost estimates decline between Scenarios C3-2075 and C5-2100 (from $130/tonne to $125/tonne) as time passes and the mitigation level stays constant. The mean estimates unexpectedly increase from $214/tonne to $221/tonne. This increase in mean costs may be driven by an expected increase in CDR between scenarios, as negative emissions are held at "at least" 1 Gt/annually in both scenarios while overall mitigation is held constant.[40]

While the benefits of aggressive climate action are likely cost-benefit justified if such action is technologically and sociopolitically feasible, respondents' estimates reflect significant uncertainty about costs, and some respondents express concerns about feasibility.[41]

Comparing responses to Question 6 and 10, we find that the median marginal cost of aggressive climate action in 2075 (i.e., Scenario C3-2075) exceeds the medians of the average costs of all CDR approaches under less aggressive climate action. The same is true for the mean marginal costs in 2075, though the mean average costs of DAC and BECCS are higher under less aggressive climate action, consistent with price reductions that could be achieved with economies of scale.

In comparison to the literature, our mean estimates are above the Fuss et al. (2018) cost forecasts, though the median estimates fall in that range. In contrast, both our mean and median fall within the range of the broader literature. Given the consistency of our median responses with Fuss et al. and the skewness of our responses, which indicate that a minority of high-cost estimates are pushing up these projections, more weight should potentially be given to our median marginal cost estimates over our mean estimates. Even so, our ranges indicate considerably more uncertainty than the estimates from Fuss et al. (2018), and potentially even more than the

---

[40] This increase in mean costs could also arise due to an unbalanced panel of respondents across questions, such that the respondents are not identical between the two questions. Alternatively, it could be driven by wide uncertainty, particularly farther into the future, which indicates that these estimates are the same from a statistical perspective.

[41] For Questions 8 to 10, we provided respondents an option to indicate that they did not wish to respond, if they perceived the net-zero or net-negative scenario in the question is infeasible. In response to Question 8, 28.5% (137 out of 481) of respondents indicated that net-zero emissions by 2075 is infeasible. In response to Question 9, 24.2% (107 out of 443) respondents indicated that net-negative emissions is infeasible over the next two centuries. In response to Question 10, 75% (258 out of 343 respondents) indicated that net-negative emissions by 2075 is infeasible. We believe that the infeasibility responses to Question 8 and 9 are more accurate, and that the responses to Question 10 should be interpreted carefully.

We believe that many respondents to Question 10 who indicated infeasibility by 2075 or 2100 did so as a "protest vote." Specifically, a substantial number of individuals commented on the difficulty of answering this question, including several who explicitly stated that was why they selected the infeasible option. Comments included: "No Opinion," "Question too complex," "complex question," "I don't feel qualified to give any estimate", and "This question is very difficult to answer…" Moreover, of the individuals who selected net-negative emissions as infeasible by 2075 (in Question 10), 156 also indicated that negative emissions were feasible over the next two centuries. Similarly, in response to Question 9 (about when net-negative could be reached using a high carbon tax and significant R&D), 75% of these respondents indicated that net-negative emissions is feasible by 2078 and 90% indicated feasibility by 2101.

existing literature. Future work using performance weights, as discussed in the next section, may address the inconsistency between the average estimates and these wide uncertainties.

QUESTION 11

Our final question asked respondents to make two near-term forecasts related to investment and capacity in carbon-capture technology (which is something of a rough proxy for CDR investment, given some overlaps in technology and use cases). This question was primarily designed as a "seed question"—once respondents' estimates can be empirically verified, we can use their relative accuracy to weight responses to other questions. We plan to conduct this analysis in future research (as of this publication, official estimates remain unavailable).

Specifically, we asked respondents to estimate the percentage change from 2022 to 2023 for two indicators:

(1) investment in carbon capture technologies by the United States energy and industrial sectors; and

(2) the annual carbon capture capacity (Mt CO_2/yr) of announced carbon capture projects around the world.

We provided respondents with 2022 data on U.S. energy- and industrial-sector investment in carbon capture technology and globally announced future capacity for carbon capture projects. At the time of the survey launch, in November 2023, official estimates of U.S. investment and announced global capacity in carbon capture projects for 2023 were unavailable. As such, respondents were unable to find reliable anchors for their estimates.

TABLE 7.

Responses to Question 11

Seed Question	Percentile	Observations	Mean	Standard Deviation	5th Percentile Estimate	50th Percentile Estimate	95th Percentile Estimate
% Increase in U.S. Investment	5	210	14.3%	21.8%	0.0%	5.0%	50.0%
	50	220	42.9%	71.6%	2.0%	20.0%	200.0%
	95	211	94.3%	184.6%	5.0%	40.0%	400.0%
% Increase in Global Capacity	5	207	16.1%	21.0%	0.0%	10.0%	50.0%
	50	214	40.5%	57.0%	3.0%	20.0%	200.0%
	95	206	83.5%	126.6%	6.0%	32.5%	350.0%

Respondents' mean and median central estimates for U.S. carbon-capture investment in 2023 were $216 million and $181 million (2022 USD), respectively. The mean estimates for our question on global carbon-capture capacity implies an increase of 106.1 to 113.9 Mt CO_2/year worldwide in 2023, while the median estimates imply an increase 90.6 to 97.3 Mt CO_2/year. As a point of reference, in Question 3 respondents estimate total CDR capacity in 2050 to be 7,600 Mt (mean) and 2,300 Mt (median).

These findings, and a close look at current investment/capacity data, underscore the scale of the future task of achieving net-zero emissions this century. Specifically, according to the median and mean responses to Question 8 of our survey, respondents believe that annual negative emissions on the scale of 25,000 Mt to 35,000 Mt, respectively, will be necessary to reach net-zero emissions by 2075. Such an expansion will require rapid increases in investment, including through future economic downturns.

Results by Subgroup

We disaggregated our sample into several subgroups based on discipline, category of CDR expertise, number of relevant publications, and other factors. We then analyzed differences in subgroup responses to see if clear patterns emerged and help determine whether the definition of expertise and relevant survey sample could be refined, either for the full survey or for particular questions. As a starting point for this analysis, we ran regressions for each of our questions controlling for numerous subgroups simultaneously in order to see whether question responses varied by group.

In general, we found few large, statistically significant differences in subgroups' views and estimates, suggesting that our selection criteria did not lead to the inclusion of less relevant respondents with divergent viewpoints. Most of the differences in subgroup responses that we did find did not carry over across multiple questions.

Of particular note, we found that there was no significant difference between respondents with one relevant CDR publication and those with multiple relevant publications, across all questions. On a small number of questions, respondents who had published in economics journals expressed different views than those who had published in interdisciplinary journals, though this result did not translate to differences by respondents' academic discipline. Respondents with a background in technology-based CDR also diverged somewhat from others on certain questions. Below, we discuss the most noteworthy, statistically significant subgroup variations. Figures showing the notable subgroup differences are available in Appendix E.

Economics Journals vs. Interdisciplinary Journals

Respondents who had published about CDR in economics journals rather than interdisciplinary journals offer somewhat more conservative estimates about the scale of future CDR activities generally, and of certain technology-related CDR approaches specifically (including BECCS, underground storage, and CO_2 utilization). This subgroup also estimates higher marginal costs for emissions reductions to reach net-zero scenarios, and these respondents are more likely to identify potential moral hazard concerns with CDR. While statistically significant, most of these differences are relatively small and were only prevalent in certain questions.

In Question 3 (estimating the quantity of CO_2 that will be removed in 2050, 2075, and 2100), we find that, holding other factors constant, respondents who had published about CDR in economics journals predict slightly lower quantities of removal in each year compared to those who had published in interdisciplinary journals. Interestingly, this difference did not align with respondents' professional disciplines—there was no significant difference between the economists in our sample and the non-economists. Those who published in economics journals also predict higher marginal costs for reaching net-zero emissions scenarios in Question 10; this finding aligns with their lower estimates for total CDR activity.

Those who published in economics journals are less bullish about certain technology-related CDR activities. In Question 4, this subgroup predicts slightly lower amounts of BECCS and higher amounts of forest-based CDR than other respondents. Consistent with this pattern, in Question 5 this group estimates that a larger amount of removed CO_2 will be stored in natural sinks and less will be stored through underground sequestration/mineralization, utilization, or enhanced oil recovery.[42]

Respondents who published in economics journals are more likely to identify potential moral hazard concerns with CDR, as a larger share of this group believes that other emissions-mitigation efforts would be significantly greater if it became clear that CDR was not viable as an offset strategy (in Question 7). This difference may reflect the fact that research in economics journals often focuses on human behavior, while some interdisciplinary journals focus more on engineering or science.

Primary Category of CDR Expertise

As part of Question 6, we asked respondents to identify the CDR approach/technology over which they have the most expertise (forest-based CDR, DAC, etc.). When forecasting the future scale of CDR activities, respondents with expertise in CDR approaches linked to natural sinks (forest, ocean, etc.) provide somewhat higher estimates for total CO_2 removal in each year compared to experts in technological/hybrid approaches (DAC and BECCS). In particular, DAC experts offer lower estimates of total CDR activity in all years.

When breaking down total estimated CDR activity by approach (Question 4), experts on each CDR approach tend to estimate somewhat higher shares for their own category. This may reflect the fact that experts have better information about their best-known approach, or it may reflect respondents' biases toward their own areas of expertise.

In Question 9, all subgroups predict that large R&D investments would have a major effect in accelerating the possibility of net-zero emissions, but DAC experts predict an especially large effect and BECCS experts also predict a higher-than-average effect.

Professional Discipline

We found very few statistically significant differences between respondents' views based on their field (engineering, natural sciences, economics, other social sciences, or other disciplines). In Question 5, economists predict that CO_2 storage in natural sinks will represent a relatively larger share of total CDR, while engineers predict relatively larger shares of CO_2 utilization and enhanced oil recovery. Compared to other subgroups, natural scientists predict slightly more underground storage and less enhanced oil recovery. In Question 9, economists were more optimistic than others about the extent to which a carbon tax (or equivalent policy) could independently speed the possibility of net-zero emissions, while other disciplines predict that adding large R&D investments would have a much greater effect.

---

[42] A larger portion of respondents who published in economics journals identified that that they had no relevant expertise on the storage and utilization of captured carbon, relative to those publishing in interdisciplinary journals.

Regional Differences

Respondents from different geographical regions expressed statistically different views for one question, on the breakdown of future CDR activities by approach (Question 4). Respondents from Central/South America predict a relatively larger share of forest-based CDR, while respondents from Asia predict a larger share of ocean-based CDR, and those in North America and Europe predict larger shares of DAC and BECCS. These differences may reflect regional research trends and/or differences in the regional availability of natural carbon sinks.

Conclusion

Our large-sample survey of researchers with expertise on CDR yielded forecasts and nuance that can complement data from the existing CDR literature. Our findings suggest that safely and efficiently scaling up CDR efforts to the levels many researchers deem necessary will be an enormous challenge, but that cost and technology challenges could be overcome as CDR efforts expand in the next few decades. Our results offer information that analysts and policymakers can use to inform expectations and policies related to CDR during this process.

Appendix A.

Full Survey Text

Page 1 of Survey

Survey on Carbon Dioxide Removal/Negative Emissions

The Institute for Policy Integrity at New York University is conducting a survey to examine the professional opinions of experts on issues related to carbon dioxide (CO_2) removal/negative emissions.* Specifically, the Institute is interested in the technological, scientific, economic, and social factors that will determine the availability and scope of carbon removal efforts.

Research on carbon removal has expanded dramatically in recent years, and these approaches have taken on a prominent role in many strategies to address climate change. While the IPCC and other groups have attempted to synthesize recent research, such attempts can be challenging given the wide range of estimates for technical constraints, cost, sociopolitical feasibility, and other factors.

Expert elicitation can often capture a greater range of opinions and clarify areas of consensus in a more nuanced manner. This survey aims to clarify experts' opinions on this topic and help update parameters used in key models, such as the integrated assessment models that calculate the social cost of carbon.

The survey should take roughly 20 minutes, and it consists of some identifying information followed by 11 questions, including eight forecasts. The aggregate results of this survey will be used in academic research and potentially distributed to journalists, but individual responses will be anonymous and confidential.

To ensure clarity, we provide definitions/context for technical terms, including all technologies/approaches, climate scenarios and variables, and feasibility and cost terms. We also provide an overview of relevant statistical concepts. This information can be accessed at any point during the survey.

We greatly appreciate your time and participation.

* A note on terminology: throughout the survey, the term "carbon removal" is used to describe the suite of approaches that can remove existing CO_2 from the atmosphere and sequester it elsewhere. These approaches are sometimes discussed as "negative emissions" technologies/approaches in the academic literature.

Page 2 of Survey

Please select all the approaches/technologies on which you have published or worked.

Please click here for definitions.

- Ocean-based carbon removal (ocean fertilization, alkalinity enhancement, coastal enhanced weathering, blue carbon management, etc.)
- Forest-based carbon removal
- Other terrestrial carbon removal (soil carbon sequestration, biochar, land-based enhanced weathering/mineralization, etc.)
- Bioenergy carbon capture and shortage (BECCS)
- Direct air capture (DAC)
- Other CO_2-specific carbon removal approaches/technologies
- None of the above

Please select all topics on which you have published or developed significant professional expertise.

- CO_2 capture
- CO_2 transportation
- CO_2 storage
- CO_2 utilization
- Sociopolitical feasibility and consequences, including environmental justice, health, and distributional issues
- Costs and economic viability
- Technological advancement: innovation, research and development, and/or demonstrations
- Deployment, diffusion, and/or learning by doing
- Government policies related to carbon removal
- Monitoring, reporting, and verification (MRV)
- Climate modeling and/or global decarbonization pathways
- Carbon offsets and accounting
- Other (please specify):
- None of the above

Which category best describes the primary position you currently hold?

- Academic
- Policy/Non-Governmental Organization
- Government
- Private sector
- Student
- Other

In which region are you currently based?

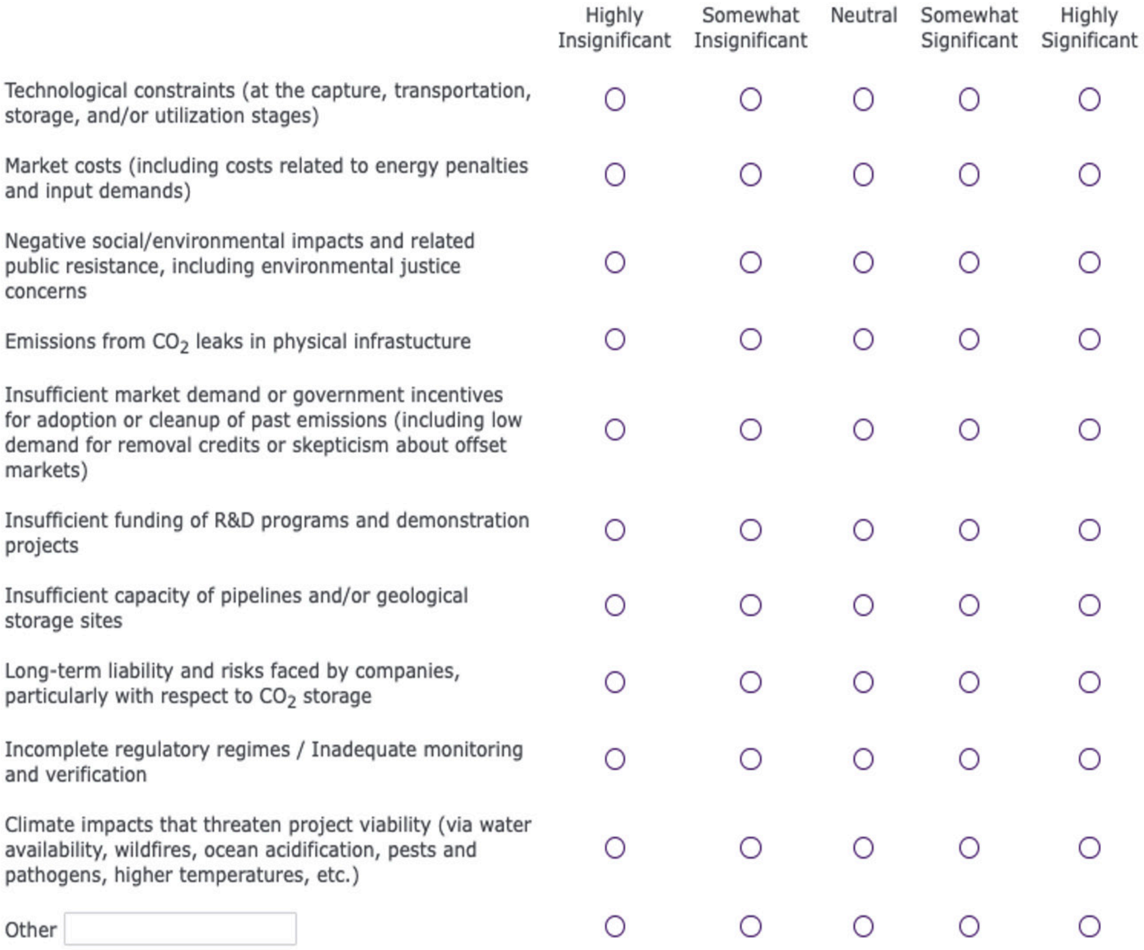
- Asia
- Central or South America
- Europe
- North Africa or the Middle East
- North America
- Oceania
- Sub-Saharan Africa

Please select the discipline of your highest professional degree (if applicable):

- Engineering
- Natural sciences
- Economics
- Other social sciences
- Other

Page 3 of Survey

Q1. How significant of a barrier to widespread carbon removal is each of the following issues?

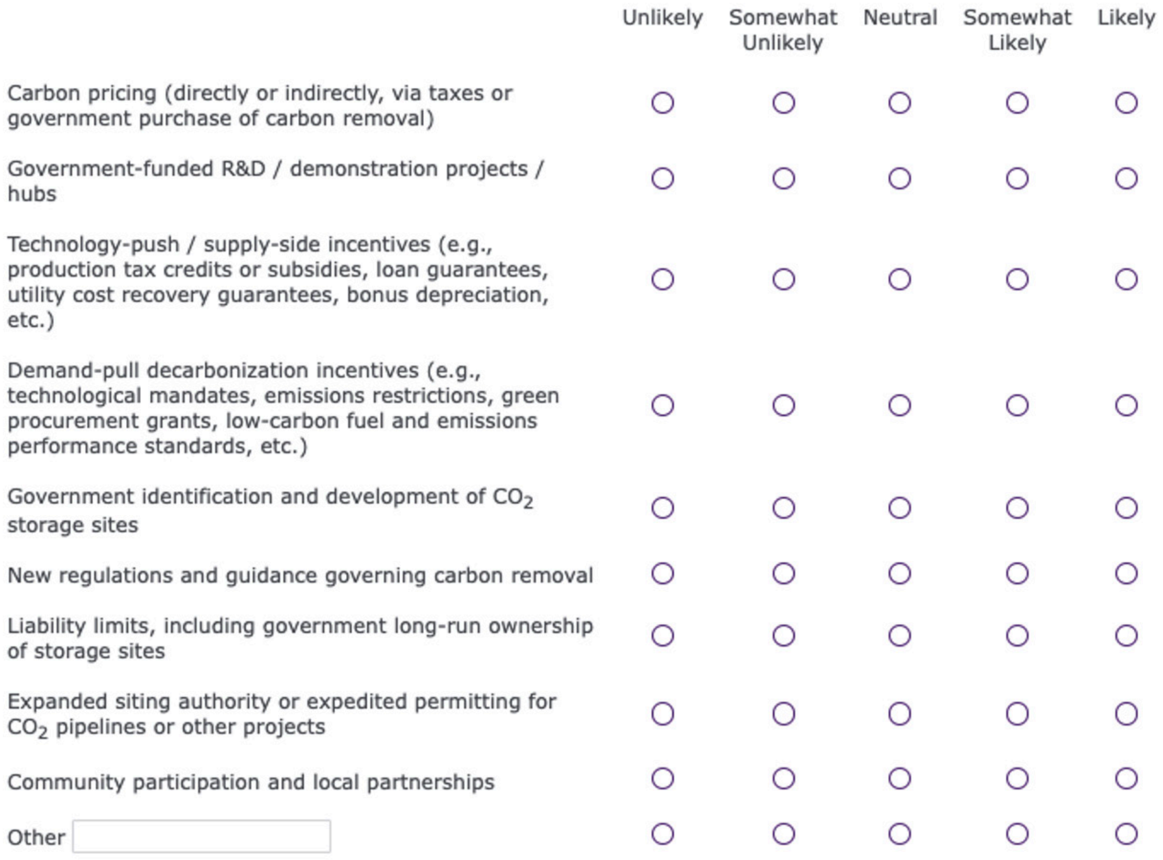


	Highly Insignificant	Somewhat Insignificant	Neutral	Somewhat Significant	Highly Significant
Technological constraints (at the capture, transportation, storage, and/or utilization stages)	○	○	○	○	○
Market costs (including costs related to energy penalties and input demands)	○	○	○	○	○
Negative social/environmental impacts and related public resistance, including environmental justice concerns	○	○	○	○	○
Emissions from CO_2 leaks in physical infrastucture	○	○	○	○	○
Insufficient market demand or government incentives for adoption or cleanup of past emissions (including low demand for removal credits or skepticism about offset markets)	○	○	○	○	○
Insufficient funding of R&D programs and demonstration projects	○	○	○	○	○
Insufficient capacity of pipelines and/or geological storage sites	○	○	○	○	○
Long-term liability and risks faced by companies, particularly with respect to CO_2 storage	○	○	○	○	○
Incomplete regulatory regimes / Inadequate monitoring and verification	○	○	○	○	○
Climate impacts that threaten project viability (via water availability, wildfires, ocean acidification, pests and pathogens, higher temperatures, etc.)	○	○	○	○	○
Other	○	○	○	○	○

Comments (optional)

Page 4 of Survey

Q2. Which policies, if implemented, are most likely to help make large-scale carbon removal viable and efficient?



	Unlikely	Somewhat Unlikely	Neutral	Somewhat Likely	Likely
Carbon pricing (directly or indirectly, via taxes or government purchase of carbon removal)	○	○	○	○	○
Government-funded R&D / demonstration projects / hubs	○	○	○	○	○
Technology-push / supply-side incentives (e.g., production tax credits or subsidies, loan guarantees, utility cost recovery guarantees, bonus depreciation, etc.)	○	○	○	○	○
Demand-pull decarbonization incentives (e.g., technological mandates, emissions restrictions, green procurement grants, low-carbon fuel and emissions performance standards, etc.)	○	○	○	○	○
Government identification and development of CO_2 storage sites	○	○	○	○	○
New regulations and guidance governing carbon removal	○	○	○	○	○
Liability limits, including government long-run ownership of storage sites	○	○	○	○	○
Expanded siting authority or expedited permitting for CO_2 pipelines or other projects	○	○	○	○	○
Community participation and local partnerships	○	○	○	○	○
Other	○	○	○	○	○

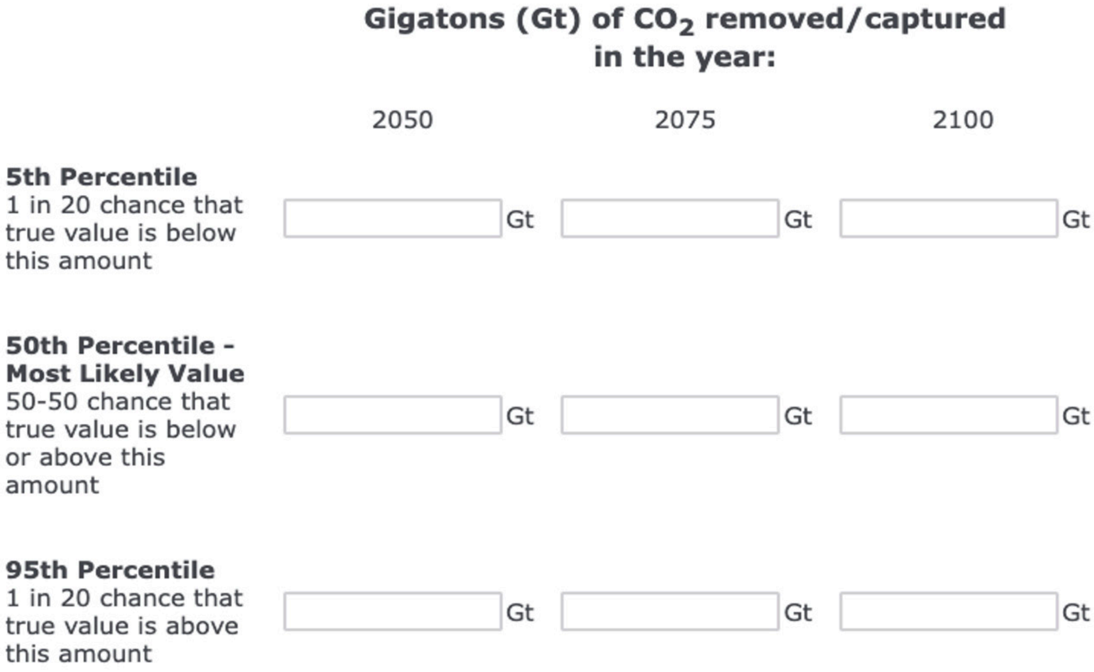
Comments (optional)

Page 5 of Survey

Q3. In each of the following years, how many gigatons of CO_2 do you think will be removed from the atmosphere (as a result of human intervention)?

Please provide a cumulative estimate that includes all carbon removal approaches that could produce "negative emissions" (including augmentation of carbon sinks, direct air capture, bioenergy carbon capture and storage, etc.). Exclude point-source capture. Please account for expected technological, sociopolitical, and economic constraints.*

To avoid overconfidence and anchoring biases, please fill out your 5th and 95th percentile estimates before providing the 50th percentile (median/most likely value). Also, please carefully consider the full range of possibilities and assess whether these events fall within or outside each of these confidence intervals.



Gigatons (Gt) of CO_2 removed/captured in the year:

	2050	2075	2100
5th Percentile 1 in 20 chance that true value is below this amount	Gt	Gt	Gt
50th Percentile - Most Likely Value 50-50 chance that true value is below or above this amount	Gt	Gt	Gt
95th Percentile 1 in 20 chance that true value is above this amount	Gt	Gt	Gt

* Reference points:

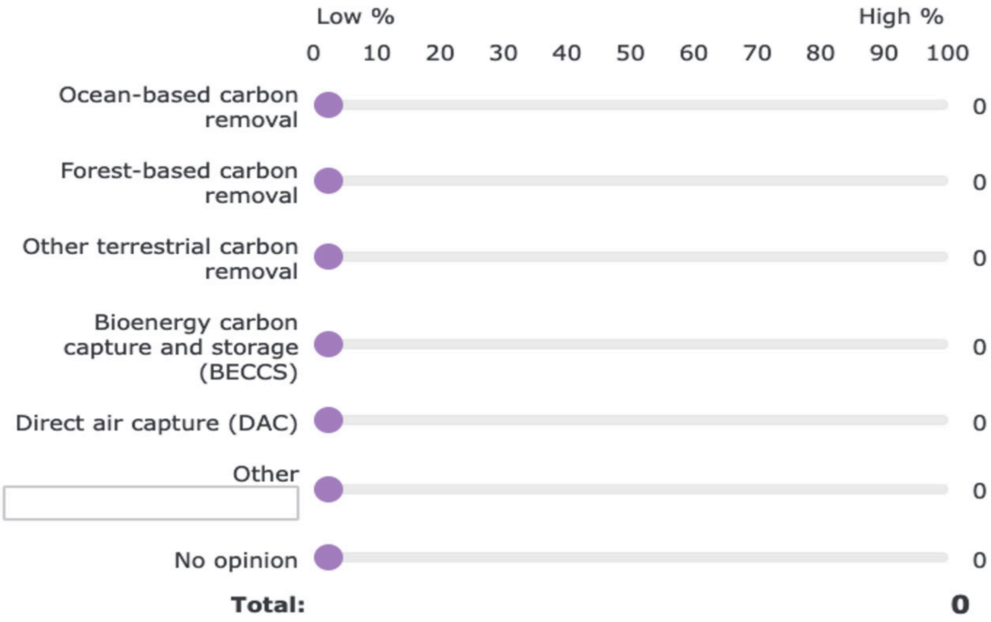
- Global energy-related CO_2 emissions in 2022: 36.8 GT (36.8 billion tonnes)
- Annual CO_2 capture capacity of largest existing Direct Air Capture facility (Orca, in Iceland): 0.000004 GT (4,000 tonnes)

Available background materials:

- Definitions of carbon removal methods
- Definitions of feasibility
- Review of the 90-percent confidence interval

Q4. Based on your 50th percentile ("most likely") estimate from question 3, please provide the percentage contribution of each category below in 2075.

Click here for definitions of carbon removal approaches.



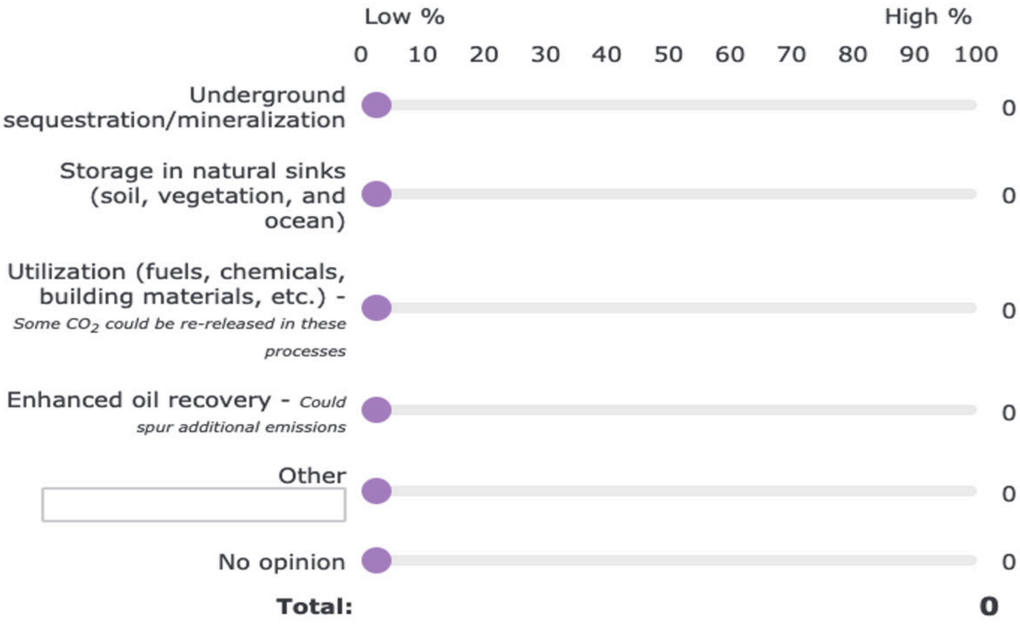
Low % High %

0 10 20 30 40 50 60 70 80 90 100

Ocean-based carbon removal	0
Forest-based carbon removal	0
Other terrestrial carbon removal	0
Bioenergy carbon capture and storage (BECCS)	0
Direct air capture (DAC)	0
Other	0
No opinion	0
Total:	**0**

If you do not have an opinion, please move the "no opinion" slider to 100%. Thank you.

Q5. Based on your estimates in questions 3 and 4, what percentage of CO_2 removed/captured do you think will be stored or used in the following ways in 2075?



Low % High %

0 10 20 30 40 50 60 70 80 90 100

Underground sequestration/mineralization	0
Storage in natural sinks (soil, vegetation, and ocean)	0
Utilization (fuels, chemicals, building materials, etc.) - *Some CO_2 could be re-released in these processes*	0
Enhanced oil recovery - *Could spur additional emissions*	0
Other	0
No opinion	0
Total:	**0**

If you do not have an opinion, please move the "no opinion" slider to 100%. Thank you.

Comments (optional)

Page 6 of Survey

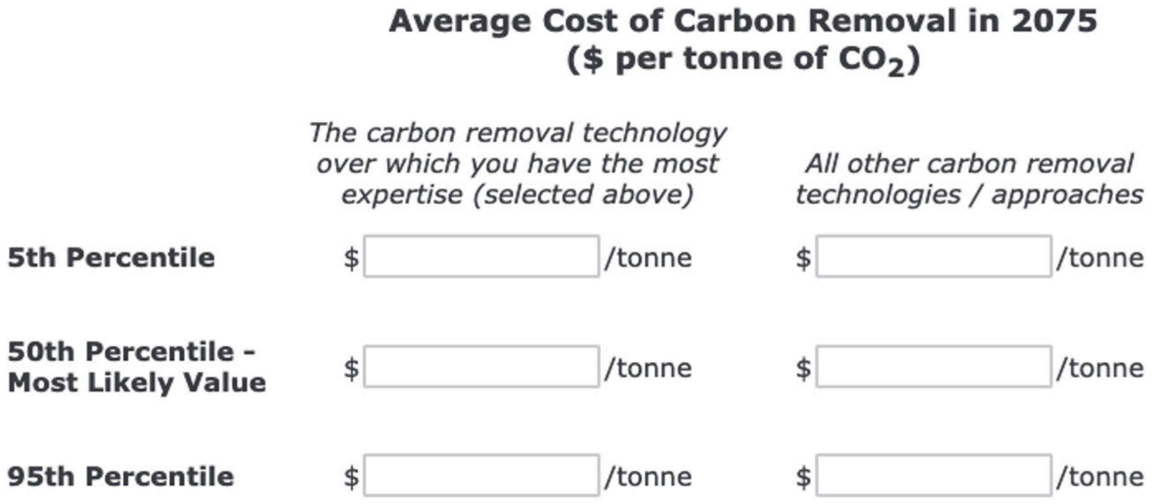
Q6. What is the carbon removal approach/technology over which you have the most expertise?

- Ocean-based carbon removal
- Forest-based carbon removal
- Other terrestrial carbon removal
- Bioenergy carbon capture and shortage (BECCS)
- Direct air capture (DAC)
- Other
- No relevant expertise

For the technology/approach you selected above, what do you think will be the average (mean) cost of carbon removal ($ per tonne of CO_2) in 2075? And what do you think will be the average cost of all other technologies/approaches?

Please factor in all market costs, including annualized capital costs, operational/management costs, and energy penalties, of all the relevant steps: capture, transportation, storage, and utilization. Please consider technological/sociopolitical constraints and climate system dynamics. Do not account for inflation when answering the question – please use current (2023) dollars.

Please fill out your 5th and 95th percentile estimates before providing the 50th percentile (most likely value), and carefully assess whether the full range of possible events fall within or outside this confidence interval.



Average Cost of Carbon Removal in 2075
($ per tonne of CO_2)

	The carbon removal technology over which you have the most expertise (selected above)	*All other carbon removal technologies / approaches*
5th Percentile	$ ☐ /tonne	$ ☐ /tonne
50th Percentile - Most Likely Value	$ ☐ /tonne	$ ☐ /tonne
95th Percentile	$ ☐ /tonne	$ ☐ /tonne

Comments (optional)

Page 7 of Survey

Q7. Under a scenario where no large-scale carbon removal approaches become viable by 2075, how do you think other global emissions-mitigation efforts would be affected?

- Other emissions-mitigation efforts would be roughly identical, regardless of the unavailability of carbon removal as an offset strategy.
- Other emissions-mitigation efforts would be significantly greater due to the unavailability of carbon removal as an offset strategy.
- Other emissions-mitigation efforts would be significantly smaller due to the unavailability of carbon removal as an offset strategy.
- Other

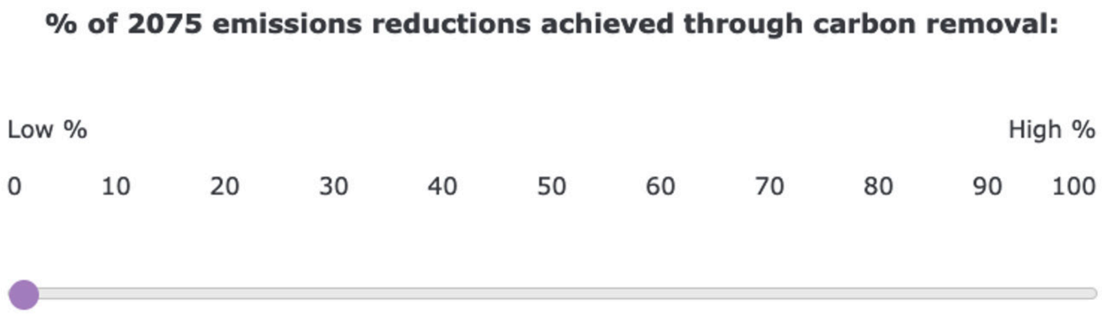
Comments (optional)

Page 8 of Survey

Q8. Models suggest that achieving global net-zero emissions in 2075 would entail mitigation of roughly 123 gigatons of CO_2 in 2075 (the difference between a business-as-usual emissions projection and a net-zero emissions projection).*

Under this 2075 net-zero GHG scenario, what percentage (of the 123 Gt mitigated) do you think would be achieved through carbon removal?

Please consider technical, sociopolitical, and economic constraints.



% of 2075 emissions reductions achieved through carbon removal:

Please check this box if you cannot answer this question because you believe that 100% mitigation in or by 2075 is infeasible.

- I cannot answer this question

---

* Based on the IPCC's emission scenario definitions, achieving net-zero emissions in 2075 is consistent with a C3 or C4 (net-zero) emissions path relative to a C8 (business-as-usual) emissions path; this would entail global mitigation of roughly 123 gigatons of CO_2 in 2075.

Available background materials:

- Definitions of emissions scenarios
- Definitions of feasibility
- Review of the 90-percent confidence interval

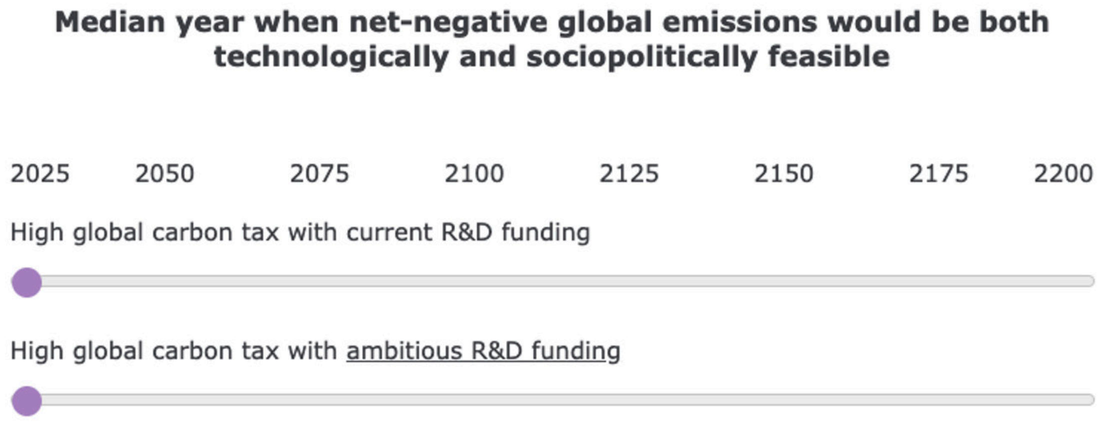
Comments (Optional)

Page 9 of Survey

Q9. When are net-negative annual CO_2 emissions likely to be feasible on a global scale, given technological and social constraints? Please specify when mitigation rates could reach more than 100% of global annual emissions under two scenarios:

(1) Aggressive global climate policy equivalent to a global carbon tax of $750/tonne (in 2023 USD) beginning in 2025 and rising annually. Current R&D funding policies remain unchanged;

(2) The same aggressive climate action in Scenario 1, but governments also commit to ambitious R&D funding for zero-emissions technologies and carbon removal equivalent to 10% of global GDP annually, beginning in 2025.



Median year when net-negative global emissions would be both technologically and sociopolitically feasible

High global carbon tax with current R&D funding

High global carbon tax with ambitious R&D funding

Please check this box if you cannot answer this question because you believe that 100% mitigation is not feasible on this timeline.

- I cannot answer this question

Context:

- *Based on policies and corporate spending on emissions mitigation before the U.S. passage of the Inflation Reduction Act, DICE-2016R2 calculates an implicit price of CO_2 of \$3/tonne for emissions in 2025 (in 2021 USD).*
- *In 2022, IEA member countries (most of continental Europe, North America, Australia, Japan, New Zealand, South Korea, and Turkey) cumulatively spent \$28 billion (2022 USD) on publicly funded R&D for low-carbon energy projects (energy efficiency, carbon capture and storage, renewable energy, nuclear, hydrogen/fuel cells, energy storage, and other cross-cutting technologies and research).*
- *The United States' energy and industrial sectors invested \$151 million in 2022 (2022 USD) in carbon capture technology, according to the Clean Investment Monitor Project.*
- *According to the IEA, the future capacity of carbon capture projects announced in 2022 was 75.5 to 81.1 Mt CO_2/yr worldwide. In comparison, global operational capacity of carbon capture was approximately 45 Mt CO_2/yr in 2022.*

Available background materials:

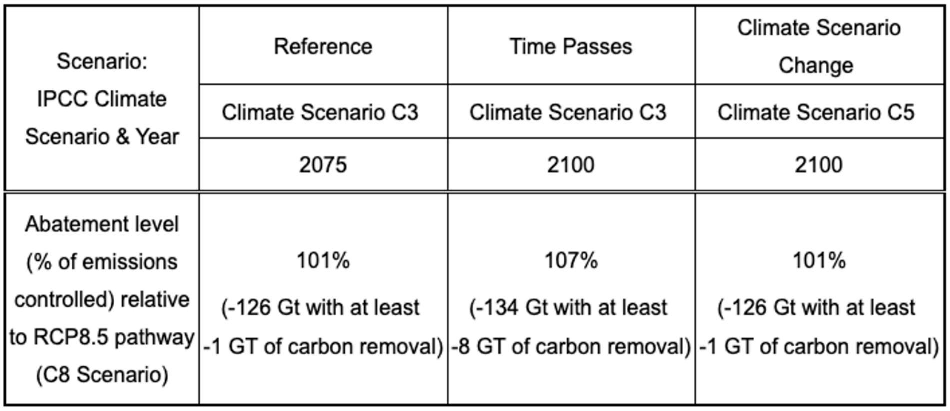
- Definitions of feasibility

Comments (Optional)

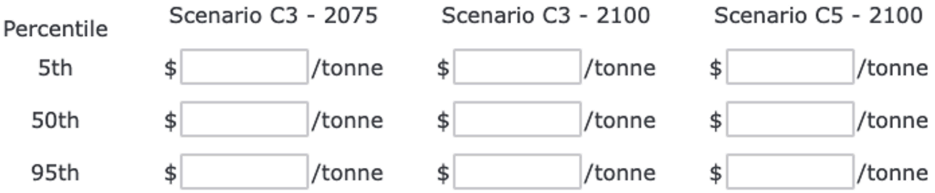
Page 10 of Survey

Q10. What is the marginal cost/price of carbon removal for the three scenarios below? The marginal cost reflects the cost of capturing, transporting, and storing/using one additional tonne of CO_2 beyond the amount specified in the three possible climate futures below. Please include annualized capital costs, operational costs, energy penalties, CO_2 leaks, and the costs of responding to social and political constraints. In an efficient market, this marginal cost equals the market price of a tonne of CO_2 removal.

Please fill out your 5th and 95th percentile estimates before providing the 50th percentile (most likely value), and carefully assess whether the full range of possible events fall within or outside this confidence interval. Do not account for inflation when answering the question – please use current (2023) dollars.



Scenario: IPCC Climate Scenario & Year	Reference	Time Passes	Climate Scenario Change
	Climate Scenario C3	Climate Scenario C3	Climate Scenario C5
	2075	2100	2100
Abatement level (% of emissions controlled) relative to RCP8.5 pathway (C8 Scenario)	101% (-126 Gt with at least -1 GT of carbon removal)	107% (-134 Gt with at least -8 GT of carbon removal)	101% (-126 Gt with at least -1 GT of carbon removal)



Percentile	Scenario C3 - 2075	Scenario C3 - 2100	Scenario C5 - 2100
5th	$ ☐ /tonne	$ ☐ /tonne	$ ☐ /tonne
50th	$ ☐ /tonne	$ ☐ /tonne	$ ☐ /tonne
95th	$ ☐ /tonne	$ ☐ /tonne	$ ☐ /tonne

Please check this box if you cannot answer this question because you believe that 100% mitigation in or by 2075 is infeasible.

- I cannot answer this question

Available background materials:

- Definitions of emissions scenarios
- Definitions of feasibility
- Definitions of costs
- Review of the 90-percent confidence interval

Comments (Optional)

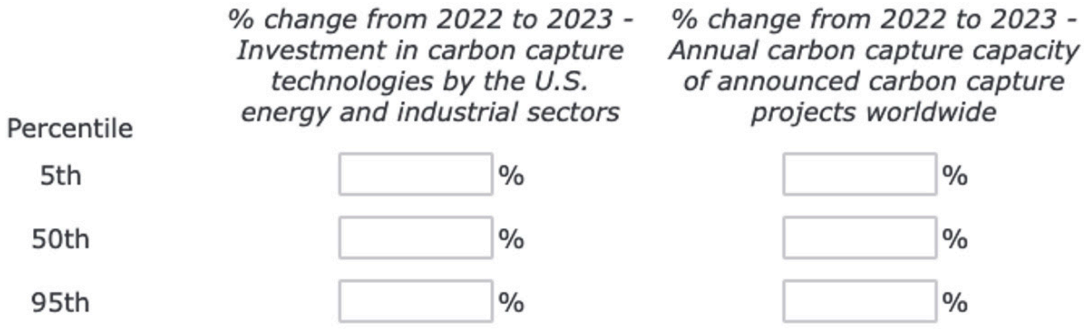
Page 11 of Survey

Q11. Please forecast the % change from 2022 to 2023 in:

(1) investment in carbon capture technologies by the United States energy and industrial sectors; and

(2) the annual carbon capture capacity (Mt CO_2/yr) of announced carbon capture projects around the world.

Answers to these questions will provide context for survey results on negative CO_2 emissions. Please fill out your 5th and 95th percentile estimates before providing the 50th percentile (most likely value), and carefully assess whether the full range of possible events fall within or outside this confidence interval. Indicate a decline with a (-) and an increase with a (+).



Percentile	*% change from 2022 to 2023 - Investment in carbon capture technologies by the U.S. energy and industrial sectors*	*% change from 2022 to 2023 - Annual carbon capture capacity of announced carbon capture projects worldwide*
5th	%	%
50th	%	%
95th	%	%

Context:

- According to the Clean Investment Monitor project, United States' energy and industrial sectors invested $151 million in carbon capture technology in 2022 (2022 USD).
- According to the IEA, the future capacity of carbon capture projects announced in 2022 was between 75.5 and 81.1 Mt CO_2/yr worldwide.

Available background materials:

- Definitions of feasibility

Comments (Optional)

Page 12 of Survey

We thank you for your time spent taking this survey.
Your response has been recorded.

Appendix B.

Journals Used to Identify Respondents

Top-Rated Journals for Negative-Emissions Research	Top-Rated Journals for Environmental Economics
Applied Energy	*American Journal of Agricultural Economics*
*Climate Policy**	*Ecological Economics*
*Climatic Change**	*Energy Economics**
Energies	*Environmental and Resource Economics*
Energy	*Journal of Environmental Economic Management*
Energy Conversion and Management	*Land Economics*
*Energy Economics**	*Resource and Energy Economics*
Energy Environment	*Review of Environmental Economics and Policy*
Energy Policy	*Journal of the Association of Environmental and Resource Economics*
Environmental Research Letters	
Environmental Science Technology	
Fuel	
Global Change Biology Bioenergy	
Global Environmental Change	
Greenhouse Gases Science and Technology	
Industrial Engineering Chemistry Research	
International Journal of Greenhouse Gas Control	
International Journal of Hydrogen Energy	
Journal of Cleaner Production	
*Nature Communications**	
Renewable Sustainable Energy Reviews	

*Three journals were identified in all four reviews of the negative emissions literatures (highlighted in green). Two journals were identified in three of these reviews (highlighted in orange). Seven journals were identified in two reviews (highlighted in yellow), and nine were identified in one review (white). Our pool focused on all journals identified by at least three reviews. In order to diversify the expertise of our sample we also included other journals if they had a general or policy focus (indicated by a *), and we included relevant articles from top-ranked environmental economics journals.*

Appendix C.

Additional Results

TABLE 8.

Estimated Gigatons of CO_2 Removed (Gt/CO_2)
in 2075 by CDR Approach and Calculation Method (Question 4)

Sample	Product of Mean Responses of Group to Questions 3 and 4		Mean of Product of Individual Responses to Questions 3 and 4	
CDR Approach	**Observations**	**Mean**	**Observations**	**Mean**
Ocean-based CDR	528	1.5	389	1.8
Forest-based CDR	528	2.4	389	2.7
Other terrestrial CDR	528	1.6	389	2.0
BECCS	528	2.7	389	2.9
DAC	528	2.3	389	2.5
Other CDR approaches/ technologies	528	0.7	389	1.2
No Opinion	528	2.0	389	0.2

Appendix D.

IPCC Climate Scenarios

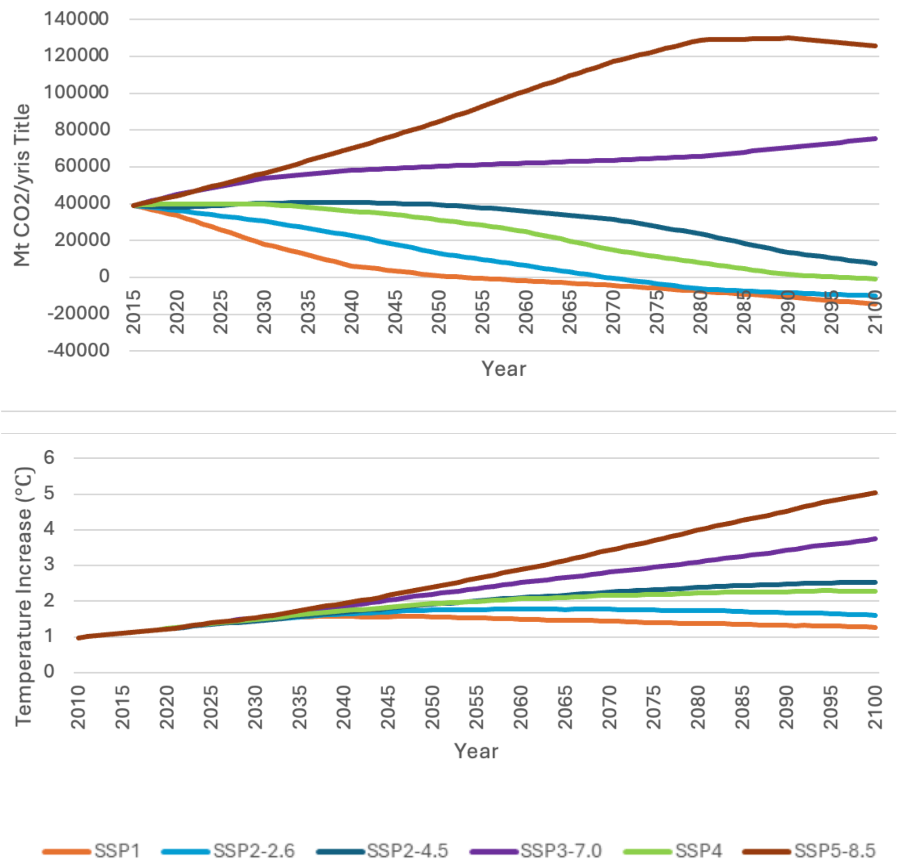
IPCC AR6 Working Group III's latest classification of climate scenarios breaks down potential emission levels into eight groups (IPCC, 2022).

Scenarios				Range of annual GHG emission (Gt of CO2e) and reduction from 2019			Net Zero emissions		Cumulative Negative Emissions (Gt)
IPCC AR6's Classification of Emission Scenarios	**Warming Levels (Global Mean Surface Air Temperature Change)***	**CMIP 6 Scenarios**	**Category Description**	**2030**	**2040**	**2050**	**CO2**	**GHG**	
C8	Above 4°C	SSP5 - 8.5	Business-As-Usual (BAU)	68 Gt to 80 Gt (-34% to -17%)	77 Gt to 96 Gt (-66% to -29%)	82 Gt to 112 Gt (-92% to -36%)	Not reached by 2100	Not reached by 2100	0 to 0
C7	Below 4°C	SSP3 - 7.0	Policy-As-Usual (PAU)	53 Gt to 69 Gt (-18% to 3%)	56 Gt to 76 Gt (-31% to 0%)	58 Gt to 83 Gt (-41% to -2%)	Not reached by 2100	Not reached by 2100	0 to 0
C6	Below 3°C (53% to 96% probability)	SSP2 - 4.5	Moderately Increased Action	50 Gt to 62 Gt (-10% to 11%)	48 Gt to 61 Gt (-14% to 14%)	45 Gt to 57 Gt (-2% to 18%)	Not reached by 2100	Not reached by 2100	0 to 0
C5	Below 2.5°C	SSP4 - 3.7	Below 2.5°C	46 Gt to 56 Gt (-1% to 18%)	36 Gt to 52 Gt (4% to 33%)	45 Gt to 57 Gt (11% to 48%)	2075 to "not reached by 2100"	2090 to "not reached by 2100"	-140 to 0
C4	Below 2°C (50% to 93% probability)	-	Below 2°C	41 Gt to 56 Gt (0% to 27%)	28 Gt to 43 Gt (20% to 50%)	19 Gt to 35 Gt (35% to 65%)	2060 to "not reached by 2100"	2080 to "not reached by 2100"	-390 to 0
C3	Likely Below 2°C with No or Limited Overshoot (68% to 97% probability)	SSP2 - 2.6	Likely Below 2°C with No or Limited Overshoot	32 Gt to 55 Gt (1% to 42%)	20 Gt to 36 Gt (34% to 63%)	13 Gt to 26 Gt (53% to 77%)	2060 to "not reached by 2100"	2075 to "not reached by 2100"	-280 to 0
C1 or C2	Below 1.5°C (15% to 73% probability)	SSP1 - 1.9	Below 1.5°C with No to Large Overshoot	21 Gt to 55 Gt (0% to 60%)	6 Gt to 34 Gt (40% to 90%)	1 Gt to 21 Gt (62% to 98%)	2035 to 2070	2050 to "not reached by 2100"	-620 to 0

** With probability in parenthesis when available from IPCC*

Here, overshoot refers to emission pathways that temporarily exceed their temperature target (usually 1.5°C or 2°C), before emissions reductions later reduce temperatures, such that the temperature target is eventually met despite a brief exceedance.

Example CO_2 and Temperature Curves, by Scenario



Source: AR6 Scenario Explorer hosted by IIASA (https://data.ece.iiasa.ac.at/ar6/#/login)

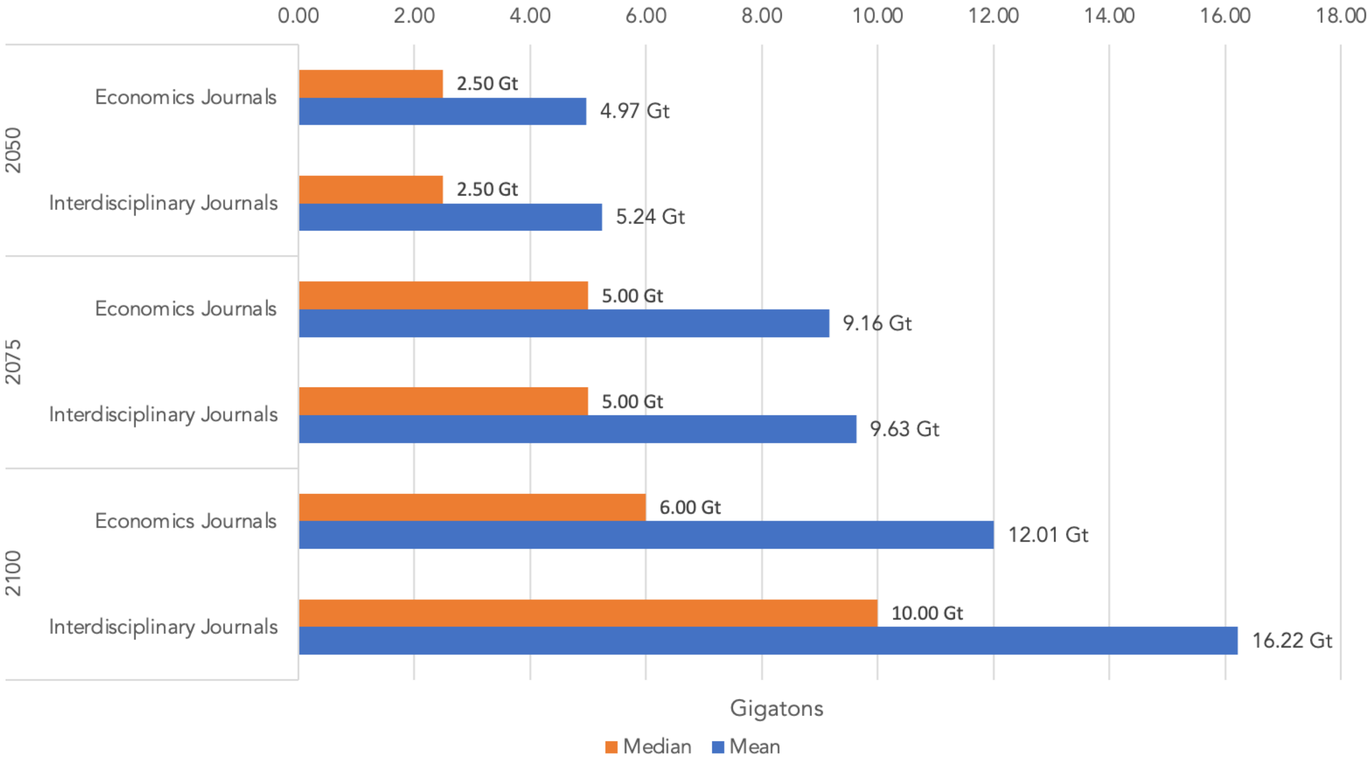
Appendix E.

Figures – Results by Subgroup

We disaggregated our sample into several subgroups based on respondents' discipline, type of CDR journal publication (economics journal vs. interdisciplinary journal), category of CDR expertise, number of relevant publications, and other factors. The figures below provide data on the most noteworthy, statistically significant subgroup variations. See the Results by Subgroup section for more discussion.

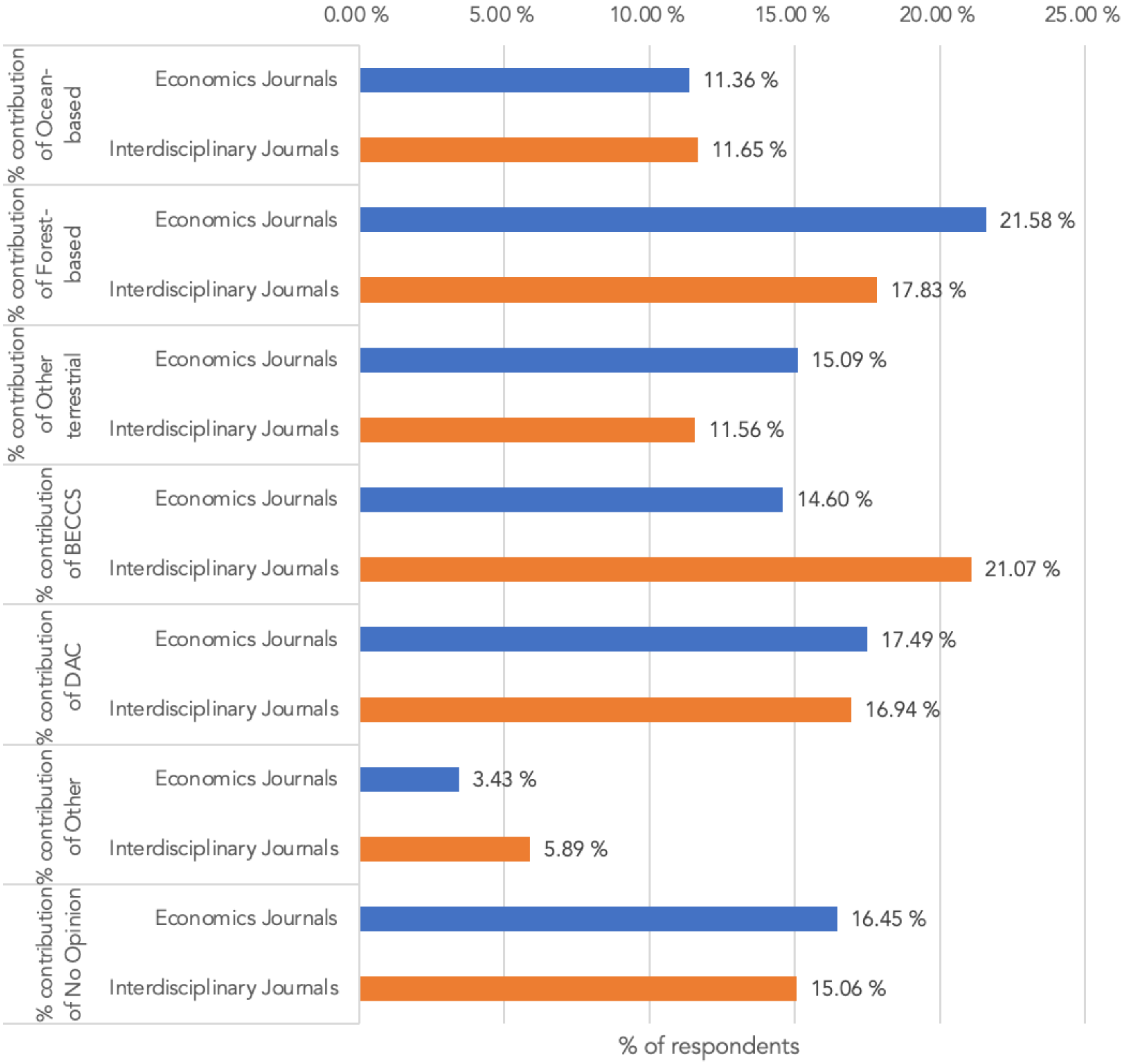
Q3. In each of the following years, how many gigatons of CO_2 do you think will be removed from the atmosphere (as a result of human intervention)?

50th percentile (most likely) value by journal type of respondents' publication(s)



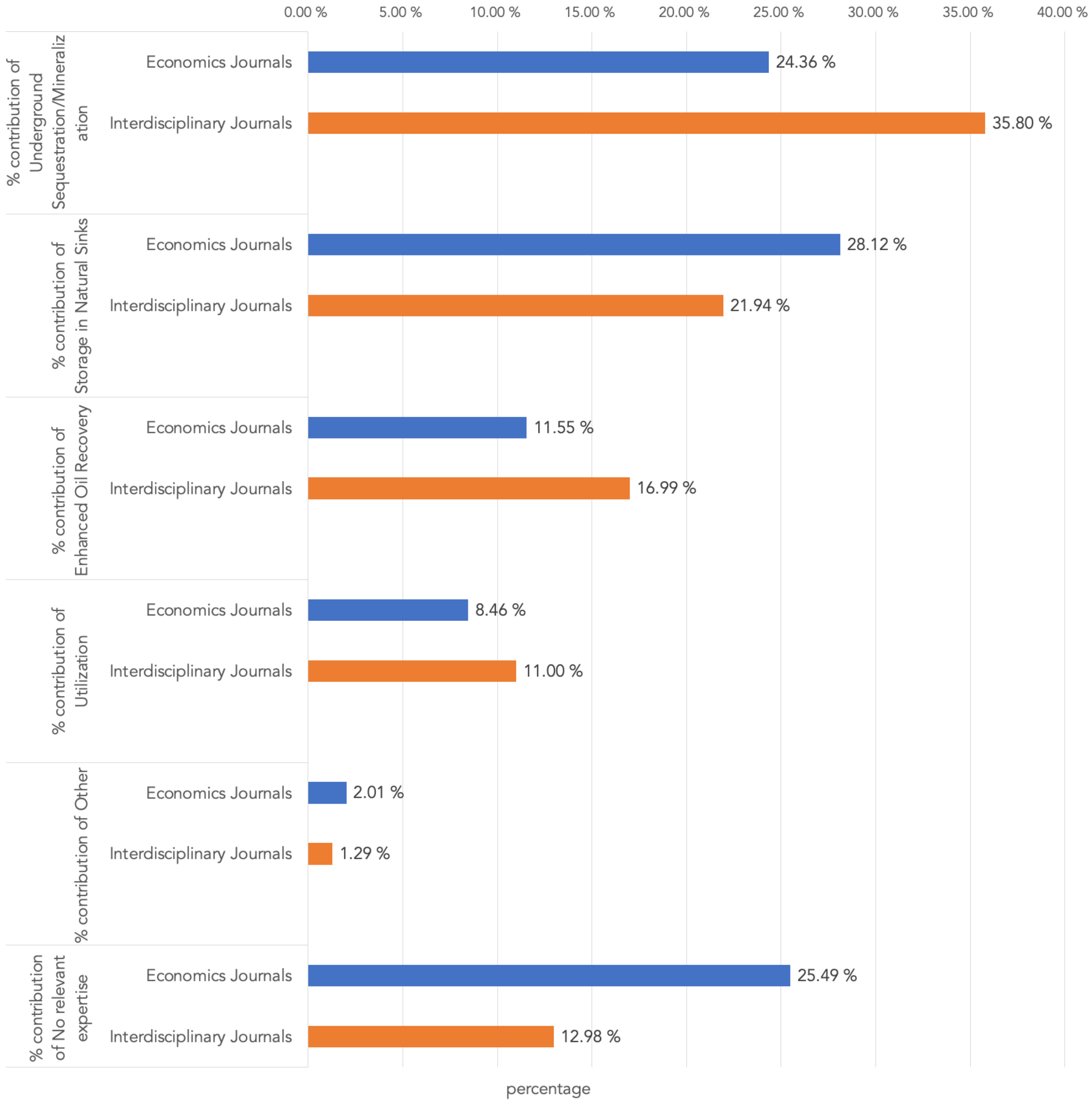
Q4. Based on your 50th percentile ("most likely") estimate from Question 3, please provide the mean percentage contribution of each category below in 2075.

By journal type of respondents' publication(s)



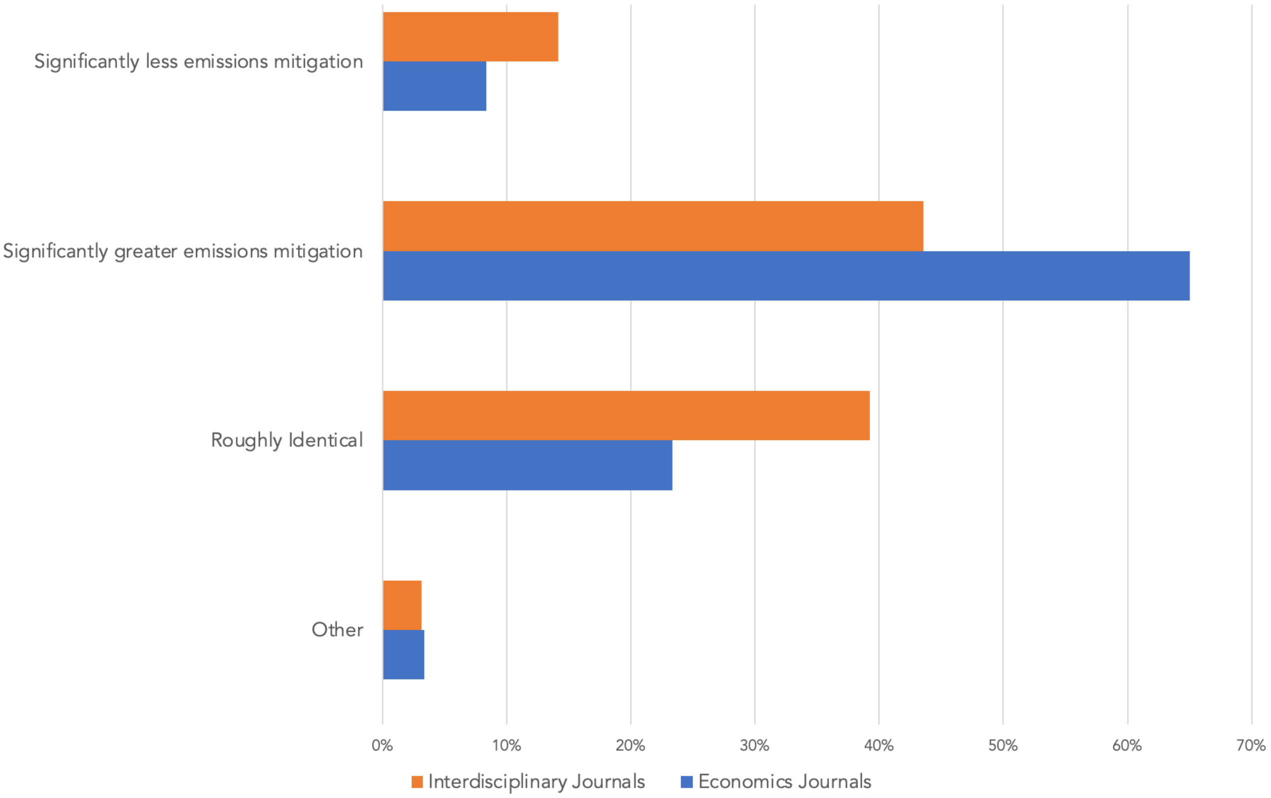
Q5. Based on your estimates in questions 3 and 4, what percentage of CO_2 removed/captured do you think will be stored or used in the following ways in 2075?

50th percentile (most likely) value by journal type of respondents' publication(s)



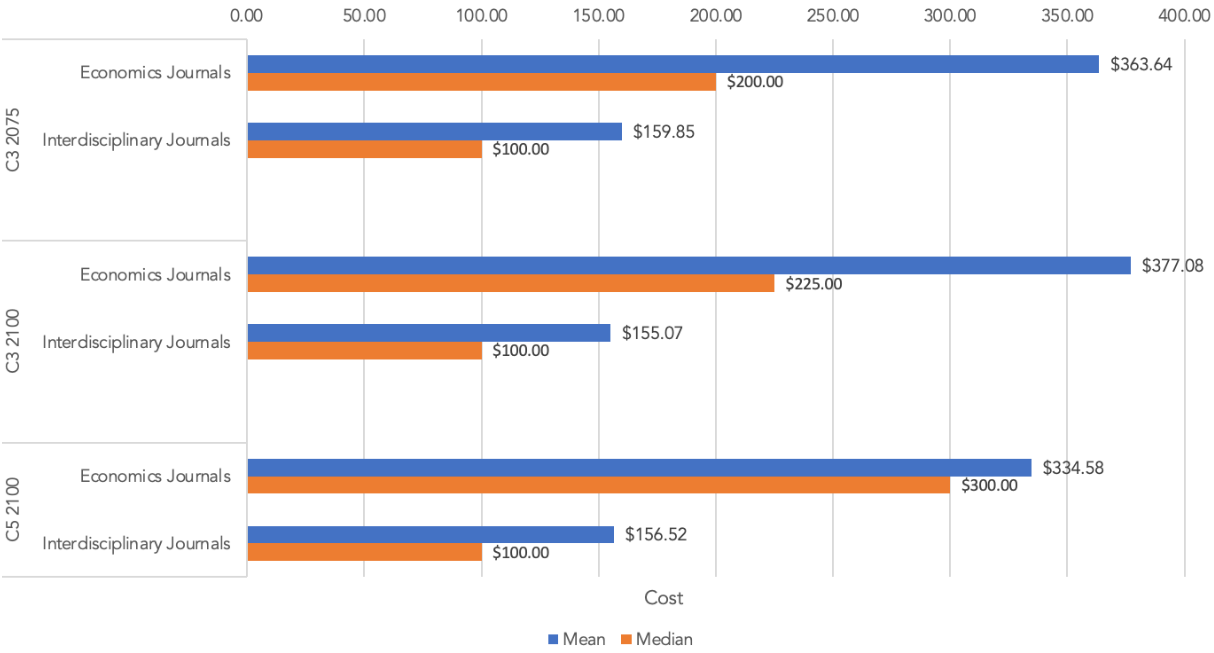
Q7. Under a scenario where no large-scale carbon removal approaches become viable by 2075, how do you think other global emissions-mitigation efforts would be affected?

50th percentile (most likely) value by journal type of respondents' publication(s)



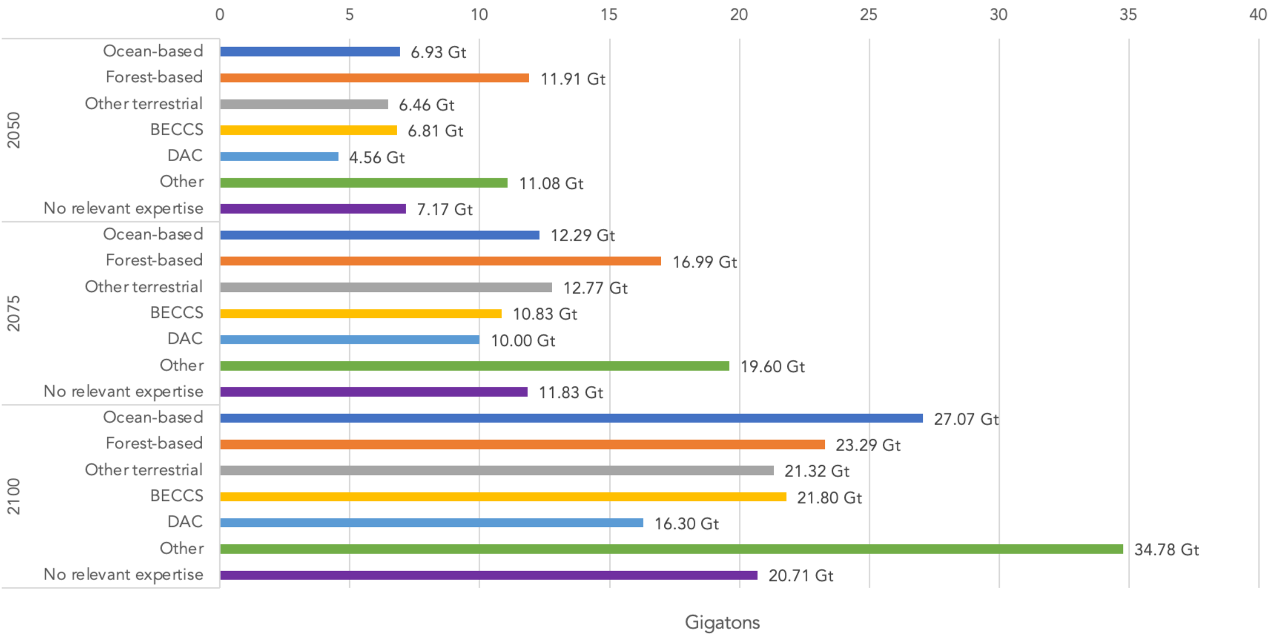
Q10. What is the marginal cost/price of carbon removal for the three scenarios below?

50th percentile (most likely) value by journal type of respondents' publication(s)



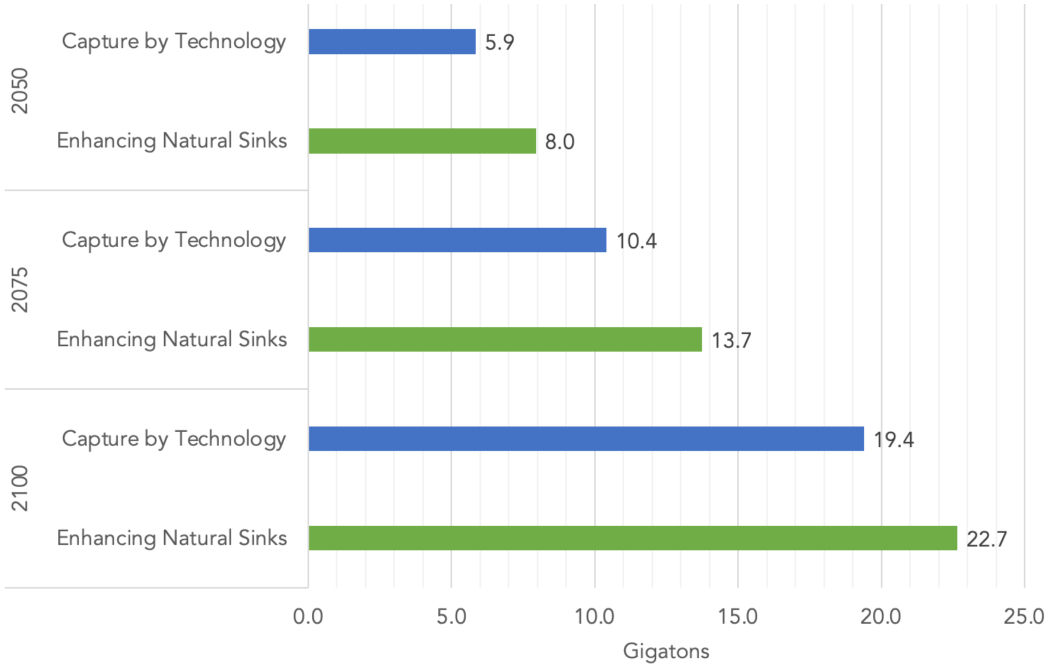
Q3. In each of the following years, how many gigatons of CO_2 do you think will be removed from the atmosphere (as a result of human intervention)?

50th percentile (most likely) value by respondent's primary category of CDR expertise



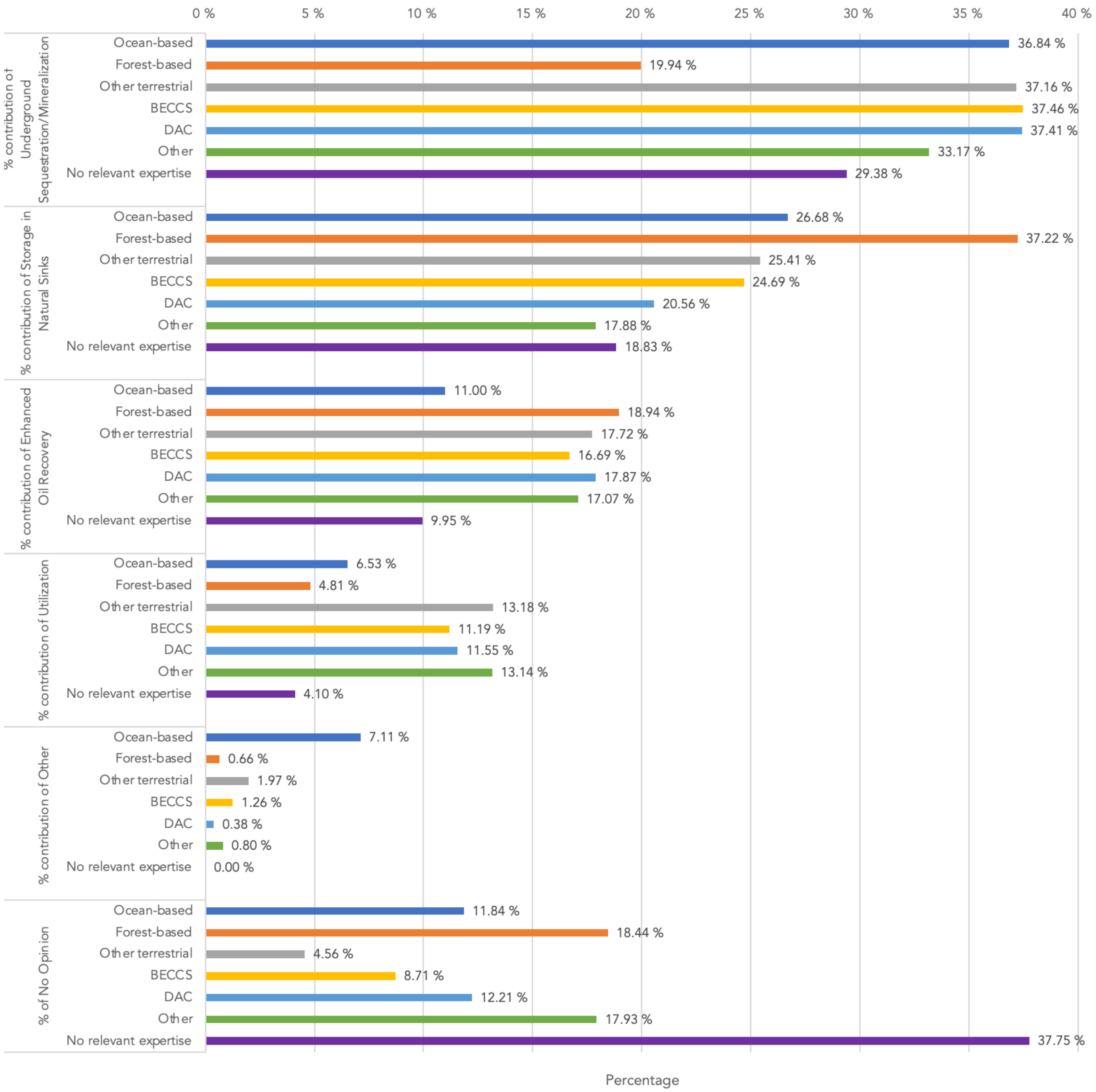
Q3. In each of the following years, how many gigatons of CO_2 do you think will be removed from the atmosphere (as a result of human intervention)?

50th percentile (most likely) value by respondent's primary category of CDR expertise, aggregated



Q5. Based on your estimates in questions 3 and 4, what percentage of CO_2 removed/captured do you think will be stored or used in the following ways in 2075?

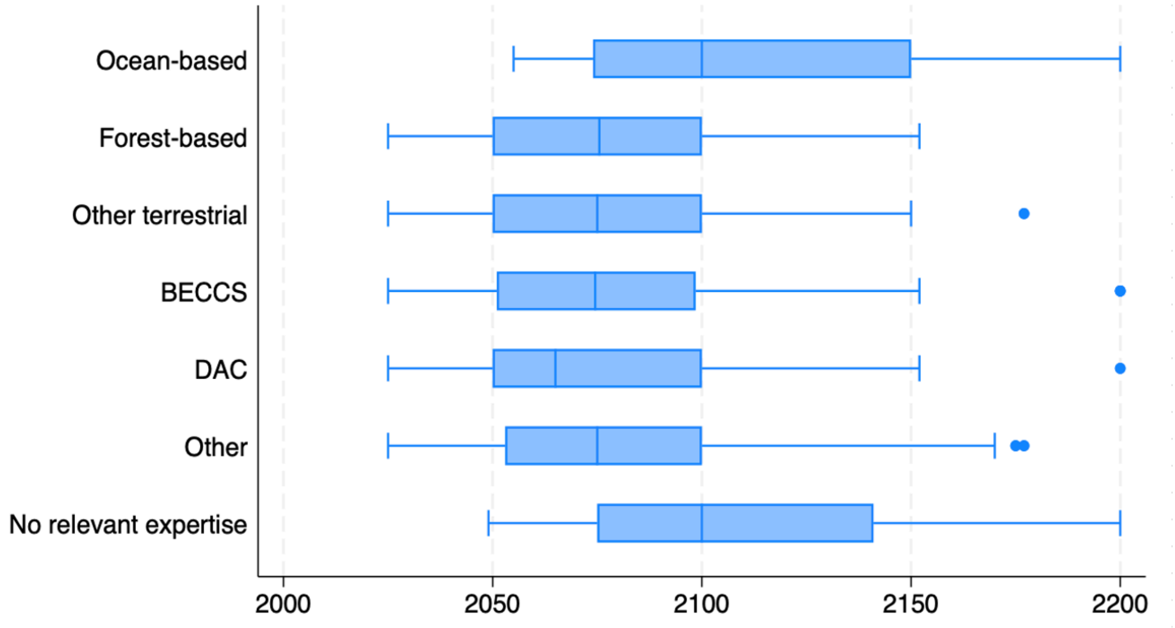
50th percentile (most likely) value by respondent's primary category of CDR expertise



Q9. When are net-negative annual CO_2 emissions likely to be feasible on a global scale, given technological and social constraints?

Scenario: High global carbon tax with current R&D funding

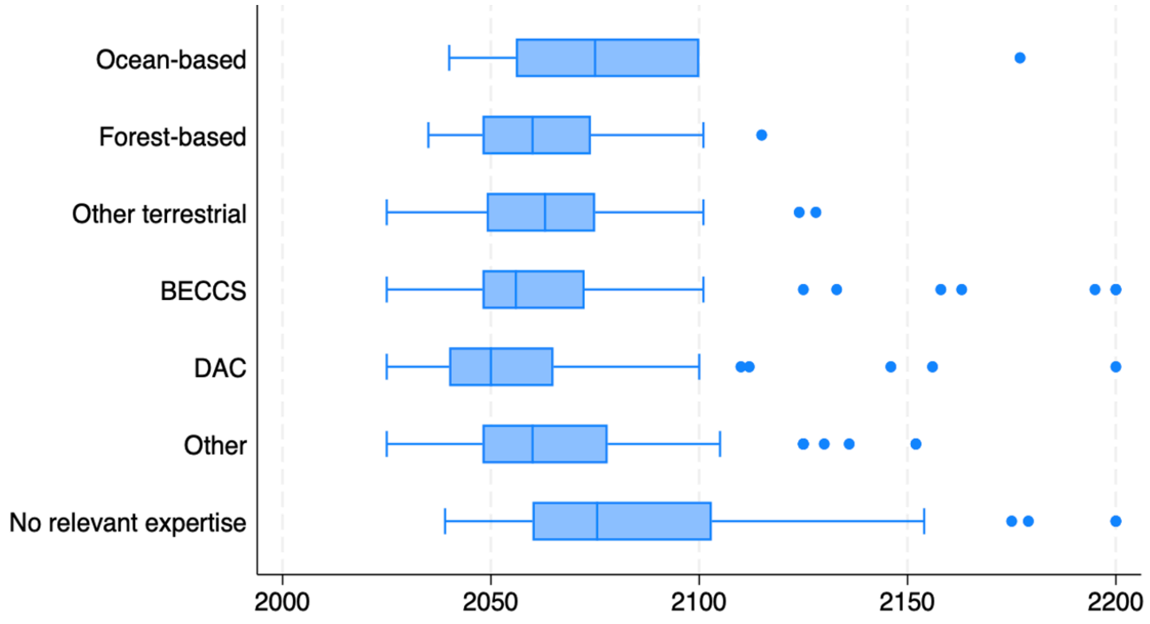
50th percentile (most likely) value by respondent's primary category of CDR expertise



Q9. When are net-negative annual CO_2 emissions likely to be feasible on a global scale, given technological and social constraints?

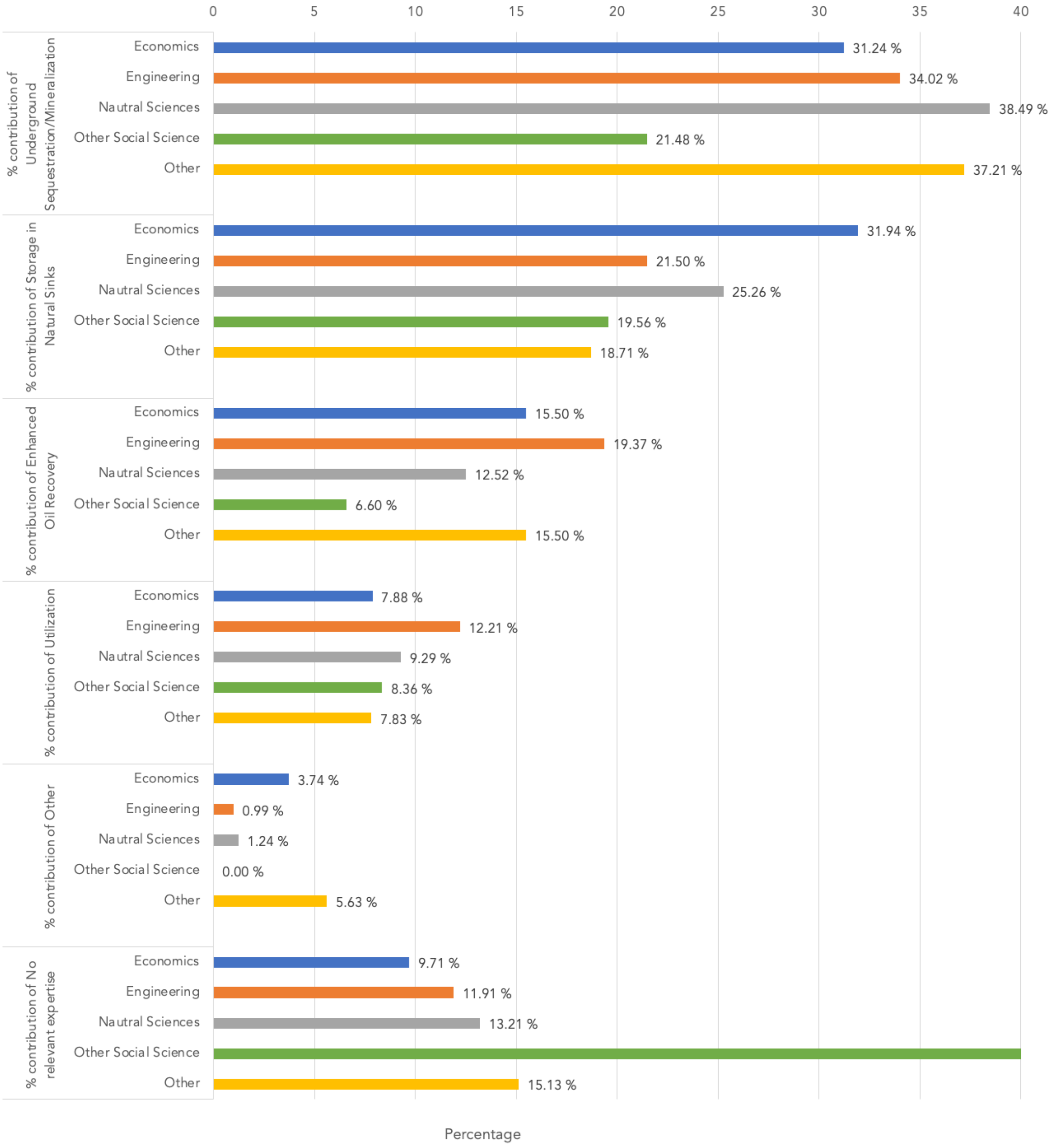
Scenario: High global carbon tax with ambitious R&D funding

50th percentile (most likely) value by respondent's primary category of CDR expertise



Q5. Based on your estimates in questions 3 and 4, what percentage of CO_2 removed/captured do you think will be stored or used in the following ways in 2075?

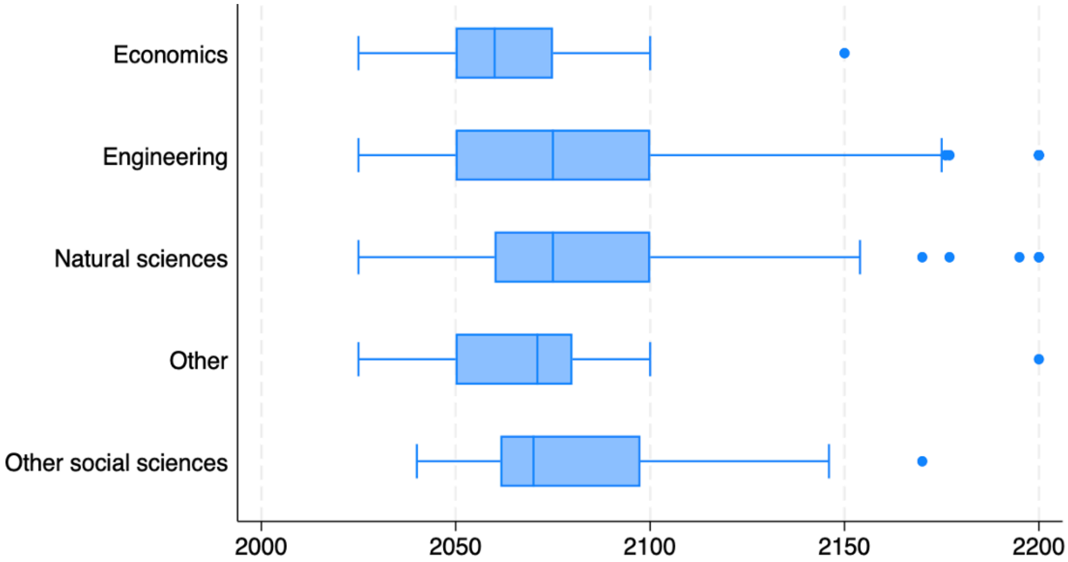
50th percentile (most likely) value by respondents' professional discipline



Q9. When are net-negative annual CO_2 emissions likely to be feasible on a global scale, given technological and social constraints?

Scenario: High global carbon tax with current R&D funding

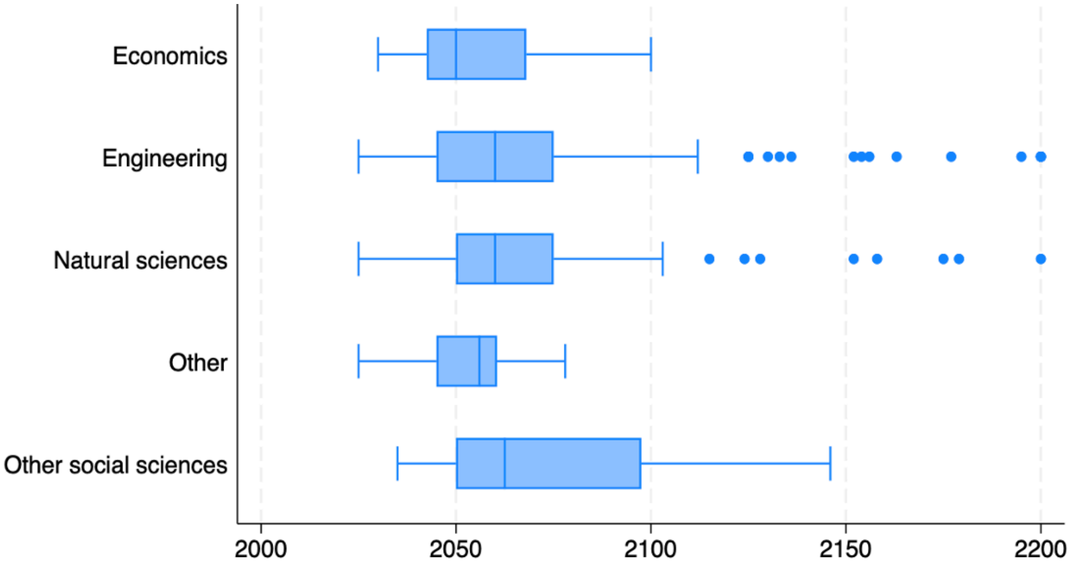
50th percentile (most likely) value by respondent's primary professional discipline



Q9. When are net-negative annual CO_2 emissions likely to be feasible on a global scale, given technological and social constraints?

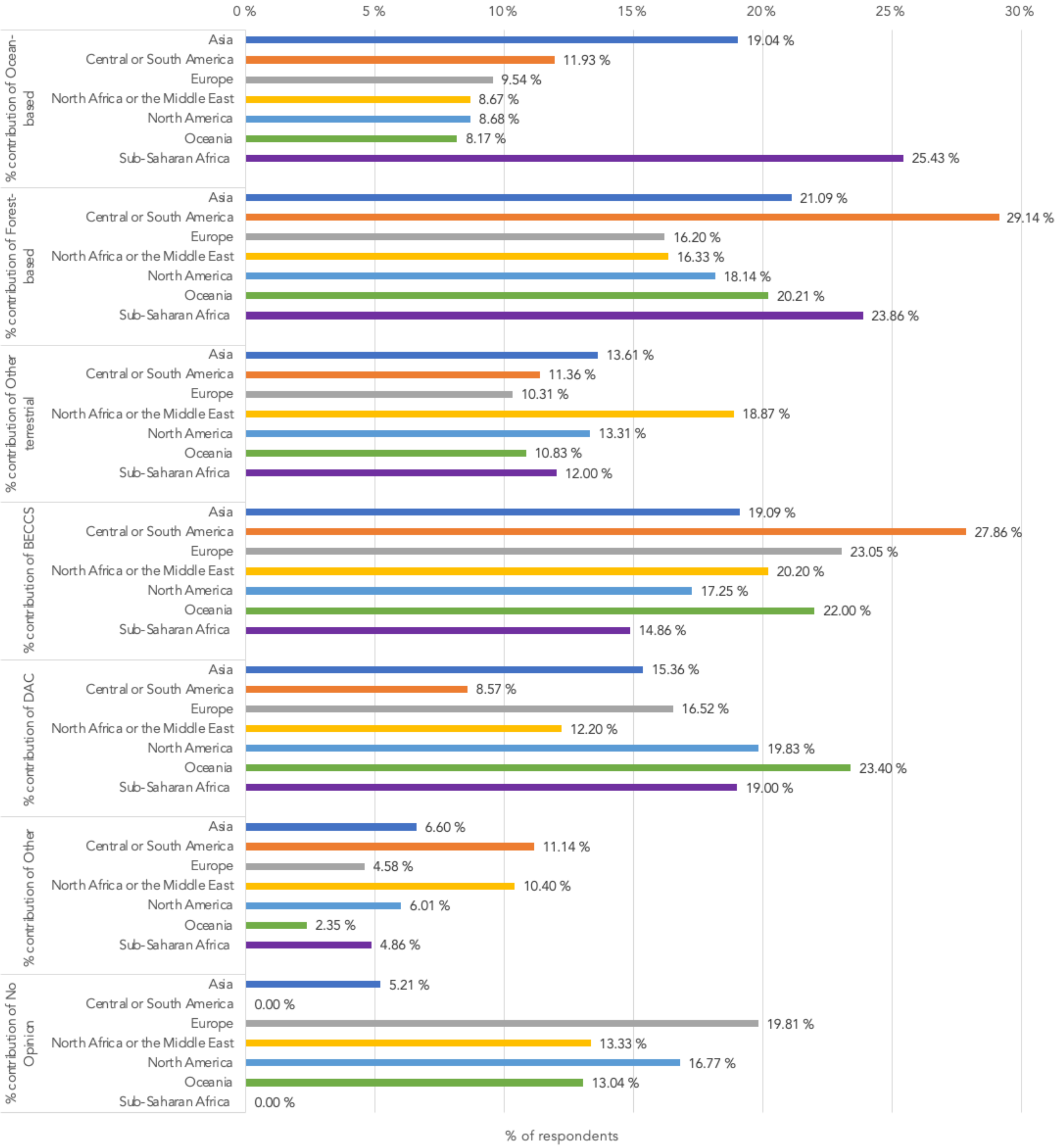
Scenario: High global carbon tax with ambitious R&D funding

50th percentile (most likely) value by respondent's primary professional discipline



Q4. Based on your 50th percentile ("most likely") estimate from Question 3, please provide the mean percentage contribution of each category below in 2075.

by respondent region



References

Aldy, J. E., Krupnick, A. J., Newell, R. G., Parry, I. W. H., & Pizer, W. A. (2010). Designing climate mitigation policy. *Journal of Economic Literature*, *48*(4), 903-934.Armstrong, J.S. (2001). Combining Forecasts. In J.S. Armstrong (Ed.). Principles of forecasting: A handbook for researchers and practitioners (pp. 417-440). Springer Science & Business Media

Anderson, M., Richardson, J., McKie, J., Iezzi, A., & Khan, M. (2011). The relevance of personal characteristics in healthcare rationing: what the Australian public thinks and why. *American journal of economics and sociology*, 70(1), 131-151.

Cooke, R. M., & Goossens, L. J. H. (1999). Procedures guide for structured expert judgment. *Project report to the European Commission, EUR, 18820*.

Fan, W., & Yan, Z. (2010). Factors affecting response rates of the web survey: A systematic review. *Computers in Human Behavior*, 26(2), 132-139.

Fuss, S., Lamb, W. F., Callaghan, M. W., Hilaire, J., Creutzig, F., Amann, T., ... & Minx, J. C. (2018). Negative emissions—Part 2: Costs, potentials and side effects. *Environmental Research Letters*, 13(6), 063002.

Gigone, D., & Hastie, R. (1997). Proper analysis of the accuracy of group judgments. *Psychological Bulletin*, 121(1), 149.

Gillingham, K., & Sweeney, J. (2010). Market failure and the structure of externalities. In *Harnessing renewable energy in electric power systems* (pp. 69-91). Routledge.

Goulder, L. H., & Schneider, S. H. (1999). Induced technological change and the attractiveness of CO_2 abatement policies. *Resource and energy economics*, *21*(3-4), 211-253.International Energy Agency. (2022). Direct Air Capture: A Key Technology for Net Zero. OECD Publishing.

[IPCC, 2022] International Panel on Climate Change. (2022). *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [P.R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, J. Malley, (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA. doi: 10.1017/9781009157926

Ison, D. C. (2017). Mitigating nonresponse error in online surveys through research-based design and delivery. *Survey Practice*, 10(2).

Li, H., Jiang, H. D., Yang, B., & Liao, H. (2019). An analysis of research hotspots and modeling techniques on carbon capture and storage. *Science of the total environment*, *687*, 687-701.

Li, J., Hou, Y., Wang, P., & Yang, B. (2018). A review of carbon capture and storage project investment and operational decision-making based on bibliometrics. *Energies*, *12*(1), 23.

Li, M., Lu, Y., & Huang, M. (2021). Evolution patterns of bioenergy with carbon capture and storage (BECCS) from a science mapping perspective. *Science of the Total Environment*, *766*, 144318.

Marcoci, A., Vercammen, A., Bush, M., Hamilton, D. G., Hanea, A., Hemming, V., ... & Fidler, F. (2022). Reimagining peer review as an expert elicitation process. *BMC Research Notes*, *15*(1), 127.

Minx, J. C., Lamb, W. F., Callaghan, M. W., Bornmann, L., & Fuss, S. (2017). Fast growing research on negative emissions. *Environmental Research Letters*, *12*(3), 035007.

Minx, J. C., Lamb, W. F., Callaghan, M. W., Fuss, S., Hilaire, J., Creutzig, F., ... & Dominguez, M. D. M. Z. (2018a). Negative emissions—Part 1: Research landscape and synthesis. Environmental Research Letters, 13(6), 063001.

McKibben, B. (2007). Warning on warming [Review of the IPCC Fourth Assessment Report]. The New York Review of Books, 15, 44-45. http://www.nybooks.com/articles/19981.

McQueen, N., Psarras, P., Pilorgé, H., Liguori, S., He, J., Yuan, M., ... & Wilcox, J. (2020). Cost analysis of direct air capture and sequestration coupled to low-carbon thermal energy in the United States. *Environmental science & technology*, *54*(12), 7542-7551.

Moore, E. J., Karplus, V. J., & Morgan, M. G. (2024). Expert elicitation of the timing and uncertainty to establish a geologic sequestration well for CO_2 in the United States. *Proceedings of the National Academy of Sciences*, *121*(1), e2307984120.

National Academies of Sciences, Engineering, and Medicine. (2019). Negative Emissions Technologies and Reliable Sequesteration: A Research Agenda. Washington DC: The National Academies Press. https://doi.org/10.17226/25259.

Oppenheimer, M., Oreskes, N., Jamieson, D., Brysse, K., O'Reilly, J., Shindell, M., & Wazeck, M. (2019). *Discerning experts: The practices of scientific assessment for environmental policy*. University of Chicago Press.

Oreskes, N., Oppenheimer, M., & Jamieson, D. (2019). Scientists have been underestimating the pace of climate change. Scientific American, 19(08). https://blogs.scientificamerican.com/observations/scientists-have-been-underestimatingthe-pace-of-climate-change/.

Pathak, M., Slade, R., Shukla, P. R., Skea, J., Pichs-Madruga, R., Ürge-Vorsatz, D., ... (2022). Technical Summary. In: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [P.R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, J. Malley, (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA. doi: 10.1017/9781009157926.002.

Rahmstorf, S., Cazenave, A., Church, J. A., Hansen, J. E., Keeling, R. F., Parker, D. E., & Somerville, R. C. (2007). Recent climate observations compared to projections. Science, 316(5825), 709-709.

Rahmstorf, S., Foster, G., & Cazenave, A. (2012). Comparing climate projections to observations up to 2011. Environmental Research Letters, 7(4), 044035. http://iopscience.iop.org/article/10.1088/1748-9326/7/4/044035/pdf.

Realmonte, G., Drouet, L., Gambhir, A., Glynn, J., Hawkes, A., Köberle, A. C., & Tavoni, M. (2019). An inter-model assessment of the role of direct air capture in deep mitigation pathways. Nature communications, 10(1), 3277.

Shayegh, S., Bosetti, V., & Tavoni, M. (2021). Future prospects of direct air capture technologies: insights from an expert elicitation survey. Frontiers in Climate, 3, 630893.

Sheehan, K. B. (2001). E-mail survey response rates: A review. Journal of Computer-Mediated Communication, 6(2), 0-0.

Smith, S. M., Geden, O., Gidden, M.J., Lamb, W. F., Nemet, G.F., Minx, J.C.…& Vaughn, N.E. (2024). The state of carbon dioxide removal 2024 – second edition.

Sovacool, B. K., Baum, C. M., & Low, S. (2022). Determining our climate policy future: expert opinions about negative emissions and solar radiation management pathways. Mitigation and adaptation strategies for global change, 27(8), 58.

Surowiecki, J. (2004). The Wisdom Of Crowds. Knopf Doubleday Publishing Group.

Sunstein, C. R. (2005). Group judgments: Statistical means, deliberation, and information markets. NYU Law Review, 80, 962. Available at: http://www.nyulawreview.org/sites/default/files/pdf/NYULawReview-80-3-Sunstein.pdf.

Vaughan, N. E., & Gough, C. (2016). Expert assessment concludes negative emissions scenarios may not deliver. Environmental research letters, 11(9), 095003.

Wang, D., Huangfu, Y., Dong, Z., & Dong, Y. (2022). Research hotspots and evolution trends of carbon neutrality—visual analysis of bibliometrics based on CiteSpace. *Sustainability*, *14*(3), 1078.

Institute *for*
Policy Integrity
NEW YORK UNIVERSITY SCHOOL OF LAW

Institute for Policy Integrity
New York University School of Law
Wilf Hall, 139 MacDougal Street, New York, New York 10012
policyintegrity.org