Supplementary Material

1 LIST OF EXPERTS

Table S1 provides the name and affiliation of the experts contacted in the exploratory phase of the project.

Table S1. List of experts in the exploratory phase

Name	Affiliation
Dan Plechaty	Climate works
Justin Ong	Clearpath
Deepika Nagabhushan	Clean Air Task Force
Howard Herzog	MIT Energy Initiative
Lori Guetre	Carbon Engineering
Julio Friedmann	Columbia University
Erin Burns	Carbon180
Whitney Herndon	Rhodium Group
Jim McDermott	Rusheen Capital Management
Klaus Lackner	Arizona State University
Jan Mazurek	Climate Works
Ryan Edwards	US Congress
Colin McCormick	Valence Strategic

2 FITTING PROBABILITY DISTRIBUTIONS

We use a triangular fitting probability distribution to the elicited 10th, 50th, and 90th percentiles (x_{10}, x_{50}, x_{90}). The triangular distribution has three parameters (a, m, b) as shown in figure S1 that define its probability distribution function:

$$f(x) = \begin{cases} 0 & x = a \\ \frac{2(x-a)}{(b-a)(m-a)} & a \leq x < m \\ \frac{2}{(b-a)} & x = m \\ \frac{2(b-x)}{(b-a)(b-m)} & m < x \leq b \\ 0 & x > b \end{cases} \tag{S1}$$

In order to find the parameters a, m, and b the fitted distribution on x_{10}, x_{50}, and x_{90} should satisfy the following cumulative probability distribution function (CDF) criteria:

$$\begin{cases} \frac{(x_{10}-a)^2}{(b-a)(m-a)} = 0.1 \\ \frac{(b-x_{90})^2}{(b-a)(b-m)} = 0.1 \end{cases} \tag{S2}$$

and one of these two conditions depending on the location of x_{50} with respect to m:

$$\begin{cases} \frac{(x_{50}-a)^2}{(b-a)(m-a)} = 0.5 & x_{50} < m \\ \text{or} & \\ \frac{(b-x_{50})^2}{(b-a)(b-m)} = 0.5 & x_{50} > m \end{cases} \tag{S3}$$

Once the parameters a, m, and b are calculated the cumulative distribution function (CDF) can be constructed by calculating the area under the triangular distribution function. After constructing the triangular distribution function based on each expert's estimate of x_{10}, x_{50}, and x_{90}, we calculate the aggregated CDF A distinguishing feature of this study is that we consider and compare the evolution of techno-economic factors over three dimensions: time (2020 vs. 2050), policy (PAU vs. 2DC), and technology (liquid solvent vs. solid sorbent). The experts were also asked to identify the key social, economic, and technical barriers in the development of DAC technologies and policies that can hinder or facilitate their future growth.

3 ADDITIONAL RESULTS

3.1 CAPEX estimates

Figure S2 shows the distribution of CAPEX estimates for each expert under both scenarios in 2020 and 2050.

Figure S3 shows the distribution of upper, middle, and lower CAPEX estimates (i.e. 10^{th}, 50^{th}, and 90^{th} percentiles) for all experts. The total number of recorded responses are indicated in red numbers at the top. The results show a very wide range of uncertainties for both technologies. Focusing on the median estimates under 2DC scenario, the experts' median estimate of the CAPEX for year 2020 is around 250 (USD/tCO2 removed). It will reduce to 125 (USD/tCO2 removed) by year 2050. Similar pattern is observed for PAU scenario, with median CAPEX reduction from 250 to 150 (USD/tCO2 removed).

3.2 OPEX estimates

Figure S4 shows the distribution of OPEX estimates for each expert under both scenarios in 2020 and 2050.

Figure S5 shows the distribution of upper, middle, and lower OPEX estimates (i.e. 10^{th}, 50^{th}, and 90^{th} percentiles) for all experts. The total number of recorded responses are indicated in red numbers at the top. Similar to the CAPEX, we can observe the median estimates under 2DC scenario where the experts' median estimate of the OPEX for year 2020 is around 275 (USD/tCO2 removed). It will reduce to 80 (USD/tCO2 removed) by year 2050. Similar pattern but with smaller reduction is observed for PAU scenario, with median CAPEX reduction from 275 to 155 (USD/tCO2 removed). As expected, the costs are reduced further under 2DC scenario compared to PAU due to the need for greater deployment of negative emissions technologies including DAC under 2DC scenario.

3.3 Total cost estimates

Figure S6 shows the triangular probability distribution of upper, middle, and lower net removal cost estimates (i.e. 10^{th}, 50^{th}, and 90^{th} percentiles) for all experts. Supplementary Table S2 summarizes the results.

Table S2. Median and uncertainty ranges for aggregate net removal cost distribution (USD/tCO_2).

Policy	Technology	Year	Lower bound	Median	Upper bound
PAU	Liquid	2020	251	453	1150
		2050	135	275	1150
	Solid	2020	336	624	1035
		2050	158	336	631
2DC	Liquid	2020	222	453	837
		2050	124	214	445
	Solid	2020	314	591	1143
		2050	77	207	691

3.4 AIC estimates

Figure S7 shows the distribution of upper, middle, and lower annual installed capacity (AIC) estimates (i.e. 10^{th}, 50^{th}, and 90^{th} percentiles) for all experts. The total number of recorded responses are indicated in red numbers at the top. The results show that experts agree on rapid expansion of DAC from the current negligible values to about 2 Gt of removed CO_2 in year 2050 under 2DC scenario. However, under PAU scenario the prospect of large deployment of DAC technologies is limited to values under 1 Gt of removed CO_2 per year.

Figure S8 shows the triangular probability distribution of upper, middle, and lower annual installed capacity estimates (i.e. 10^{th}, 50^{th}, and 90^{th} percentiles) for all experts. Supplementary Table S3 summarizes the results.

Table S3. Median and uncertainty ranges for aggregate AIC distribution ($MtCO_2$).

Policy	Lower bound	Median	Upper bound
PAU	48	240	1336
2DC	185	1692	5863

3.5 Physical requirements

Figure S9 shows the results of the survey for combined heat and electricity requirements for both technologies. Liquid solvent technologies in general require more heat during the regeneration process. Processing solid sorbent technologies on the other hand is less energy intensive and it requires lower temperature.

Temperature requirements show small variations between 2020 to 2050 for solid sorbent technologies. The median estimate for both years is around 100°C which is again at the higher end of the NAS range (67-100°C). The median estimate for year 2050 stays at the same level indicating that the experts foresee little feasible improvements in temperature requirements over the next few decades. For the liquid solvent systems the temperature requirements re much higher and therefore, the median estimate in 2020 is around 900°C which is in line with the NAS range (900-905°C). The projections for 2050 indicate a reduction to 800°C for liquid solvent technologies.

In terms of land requirements, most experts who chose solid sorbent, provided the median estimate of about 1 $km^2/MtCO_2$ for year 2020 and much lower estimates for year 2050. However, the median estimate for liquid solvent technology is around 2 $km^2/MtCO_2$ for year 2020 and 2050. The IAM studies have assumed similar range of 0.1 to 1.5 $km^2/MtCO_2$ for their analysis (Realmonte et al., 2019).

3.6 Geographic distribution

The experts then asked to project how DAC facilities will be distributed in different geographical locations in the world. Figure S10 demonstrates the projected distribution of DAC facilities in 2050 in major geopolitical areas. According to the collective opinion of the experts, North America with 27% of the total installed capacity will provide the most hospitable environment for future DAC plants. Europe and Middle East will each get a share of about one fifth of future installed capacity and China's share will be around 16% of the total global installed capacity.

4 SURVEY QUESTIONS

The following is a PDF version of an online survey.

REFERENCES

National Academies of Sciences Engineering and Medicine (2019). *Negative emissions technologies and reliable sequestration: A research agenda* (National Academies Press)

Realmonte, G., Drouet, L., Gambhir, A., Glynn, J., Hawkes, A., Köberle, A. C., et al. (2019). An inter-model assessment of the role of direct air capture in deep mitigation pathways. *Nature communications* 10, 1–12

4.1 Figures

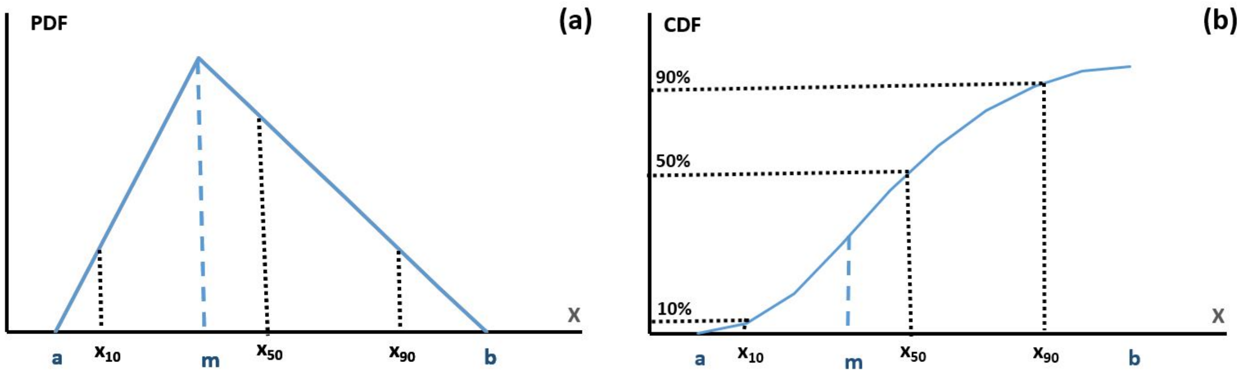

Figure S1. Schematic probability distribution function (PDF) and cumulative probability distribution function (CDF) of a triangular distribution constructed from 10th, 50th, and 90th percentiles (x_{10}, x_{50}, and x_{90}).

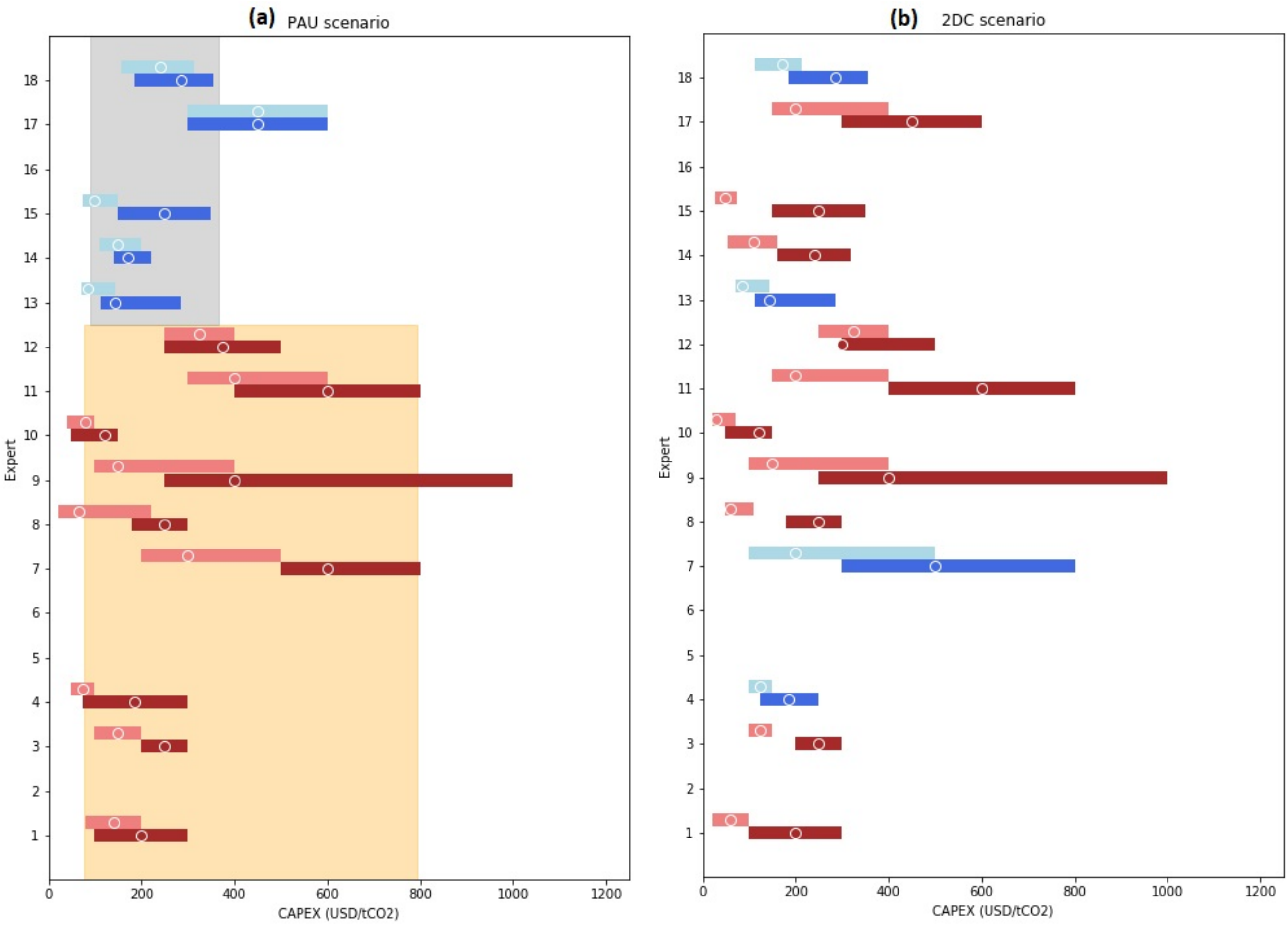

Figure S2. CAPEX estimates (50th, 90th, and 10th percentiles) for solid sorbent (red bars) and liquid solvent (blue bars) technologies under PAU and 2DC scenarios. The results are reported for 2020 (dark colors) and 2050 (light colors) for each expert. The orange and gray boxes indicate the range of values reported in the reports by the National Academy of Sciences (National Academies of Sciences Engineering and Medicine, 2019) for solid sorbent and liquid solvent technologies respectively. Experts 2, 5, 6, and 16 did not provide answers to the cost estimate questions. Experts 13 and 18 had provided the overnight CAPEX, we converted those numbers to annualized values assuming 12% recovery rate over 30 years.

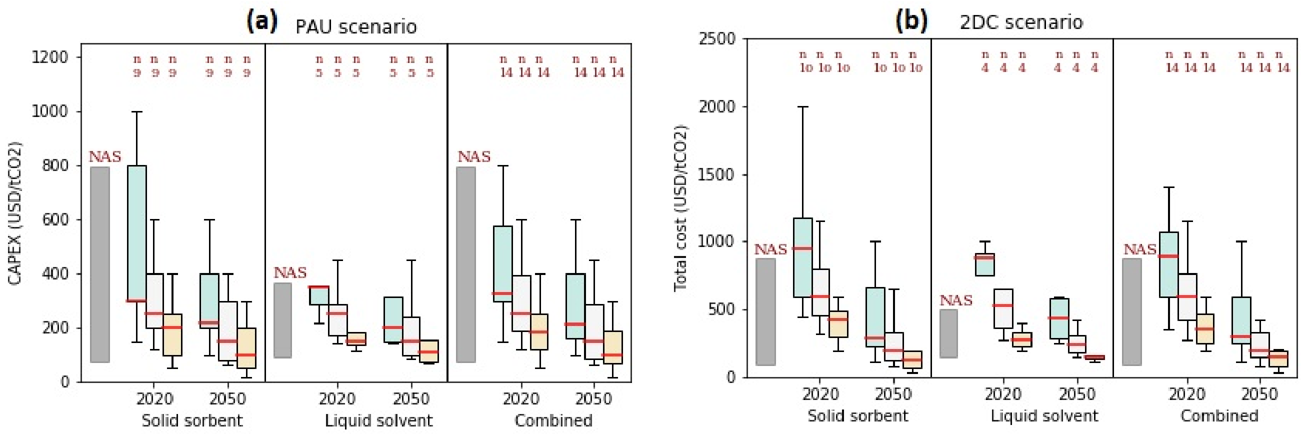

Figure S3. CAPEX estimates for solid sorbent and liquid solvent technologies under PAU and 2DC scenarios. The results are reported for two years (2020 and 2050). The green, white, and range boxes show the high, median, and low estimates respectively. The box plots show first, second (median), and third quartiles of the distribution. The whiskers indicate the maximum and minimum values. The gray box indicate the range of values reported in the reports by the National Academy of Sciences (National Academies of Sciences Engineering and Medicine, 2019). The numbers at the top indicate the number of recorded responses in each category.

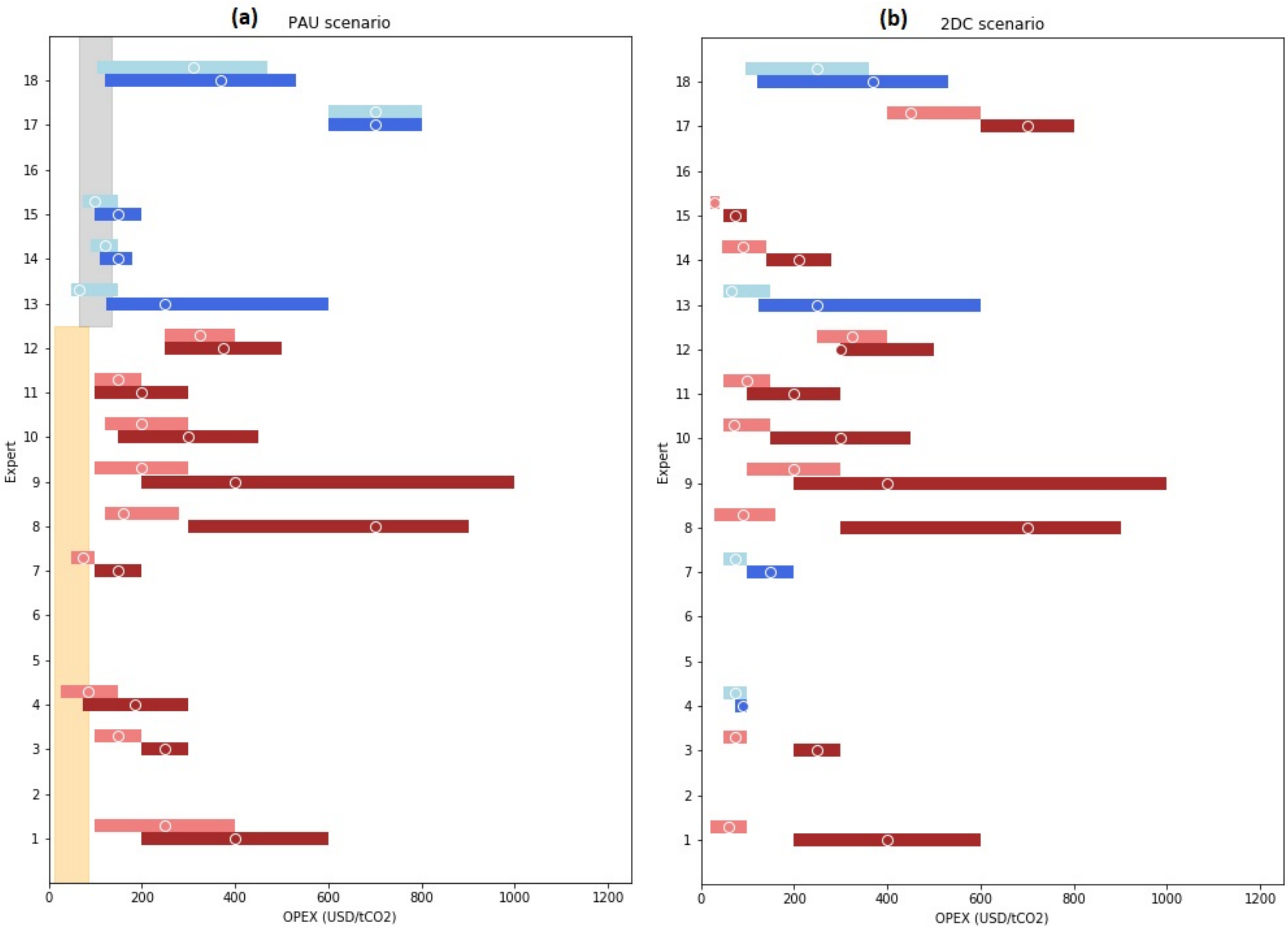

Figure S4. OPEX estimates (50th, 90th, and 10th percentiles) for solid sorbent (red bars) and liquid solvent (blue bars) technologies under PAU and 2DC scenarios. The results are reported for 2020 (dark colors) and 2050 (light colors) for each expert. The orange and gray boxes indicate the range of values reported in the reports by the National Academy of Sciences (National Academies of Sciences Engineering and Medicine, 2019) for solid sorbent and liquid solvent technologies respectively. Experts 2, 5, 6, and 16 did not provide answers to the cost estimate questions.

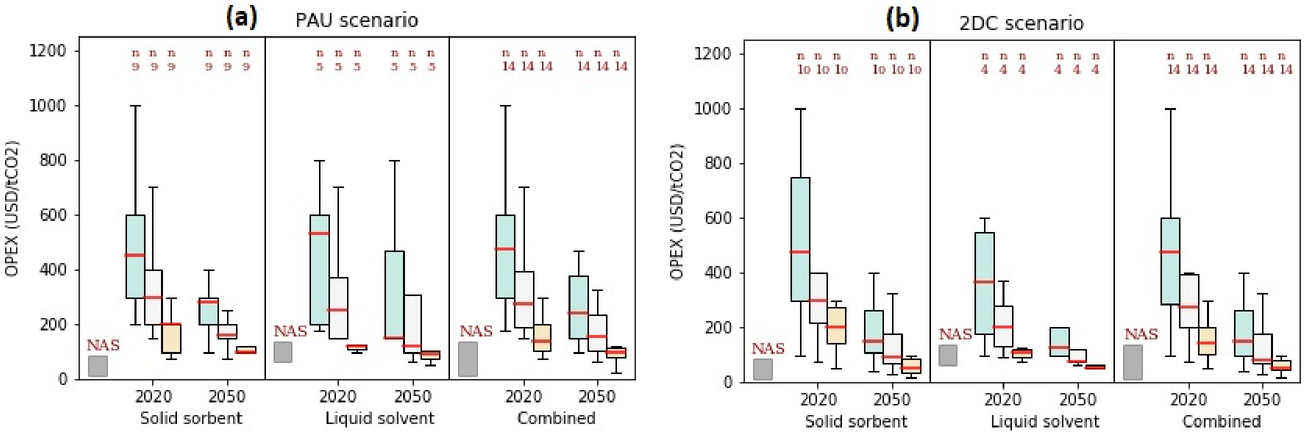

Figure S5. OPEX estimates for solid sorbent and liquid solvent technologies under PAU and 2DC scenarios. The results are reported for two years (2020 and 2050). The green, white, and range boxes show the high, median, and low estimates respectively. The box plots show first, second (median), and third quartiles of the distribution. The whiskers indicate the maximum and minimum values. The gray box indicate the range of values reported in the reports by the National Academy of Sciences (National Academies of Sciences Engineering and Medicine, 2019). The numbers at the top indicate the number of recorded responses in each category.

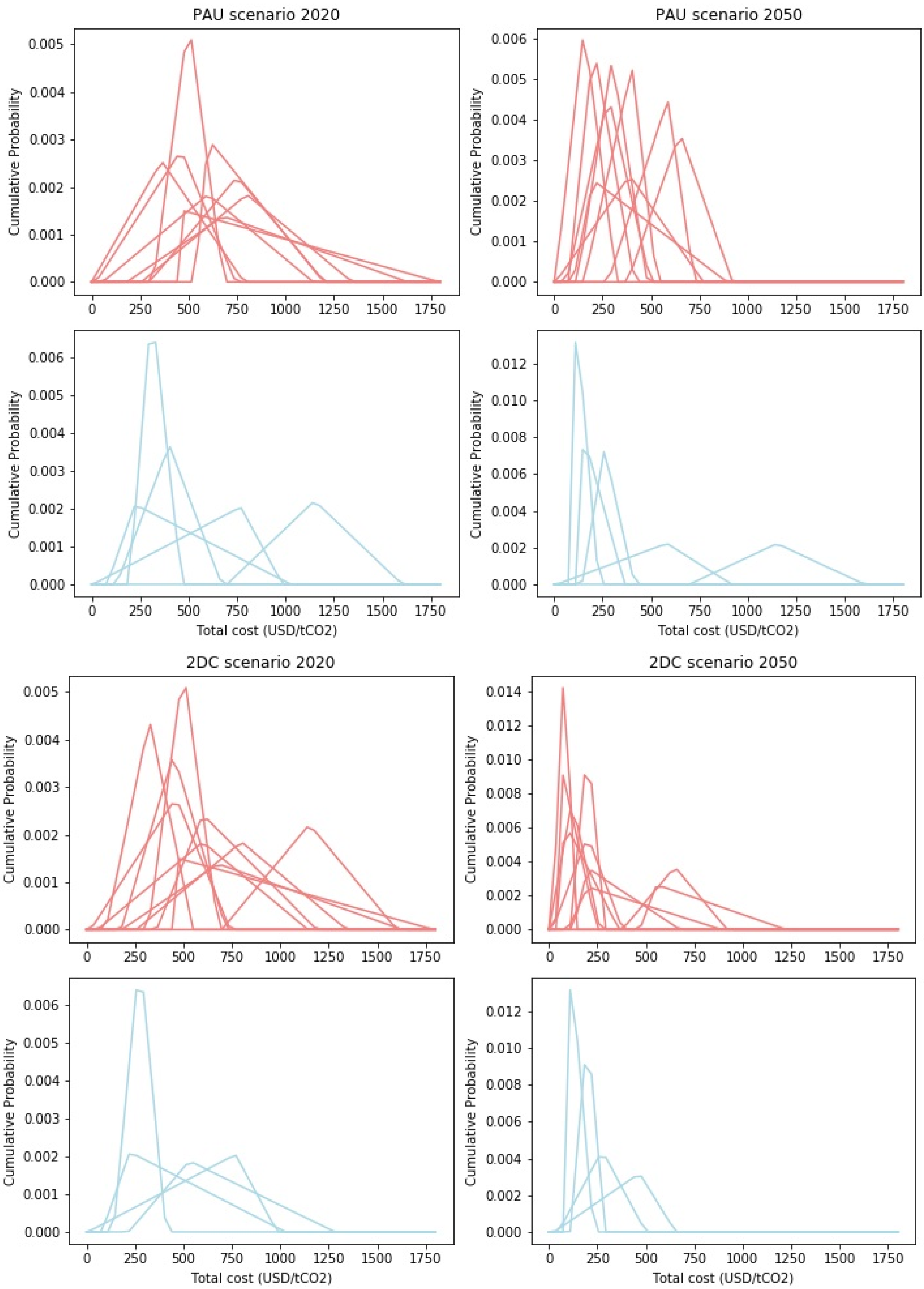

Figure S6. Probability distribution functions (PDF) for net removal cost for each expert. Probability distributions are triangular fit to 10th, 50th, and 90th percentiles for solid sorbent (red lines) and liquid solvent (blue lines) technologies under PAU and 2DC scenarios.

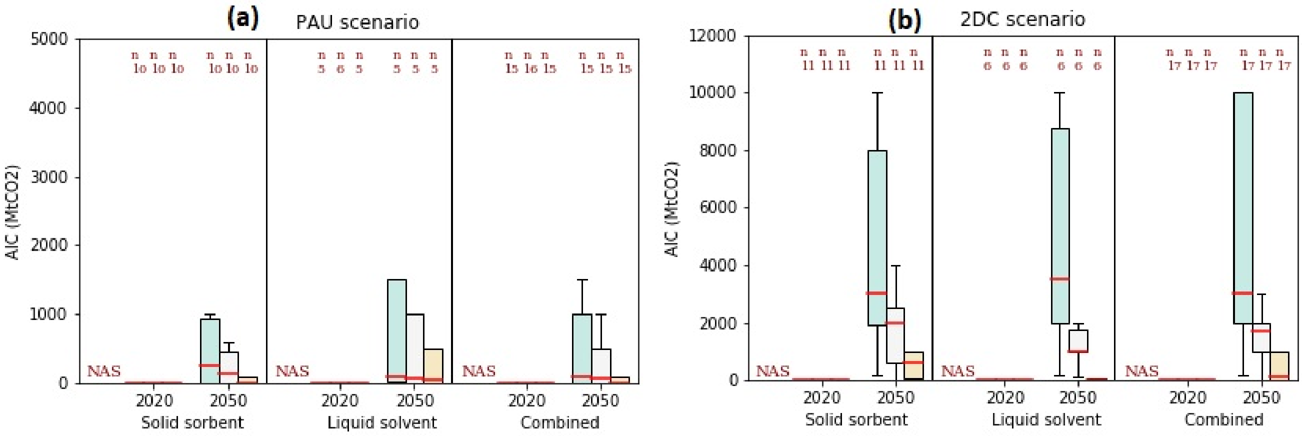

Figure S7. Annual installed capacity (AIC) for solid sorbent and liquid solvent technologies under PAU and 2DC scenarios. The results are reported for two years (2020 and 2050). The green, white, and range boxes show the high, median, and low estimates respectively. The box plots show first, second (median), and third quartiles of the distribution. The whiskers indicate the maximum and minimum values. The gray box indicate the range of values reported in the reports by the National Academy of Sciences (National Academies of Sciences Engineering and Medicine, 2019). The numbers at the top indicate the number of recorded responses in each category.

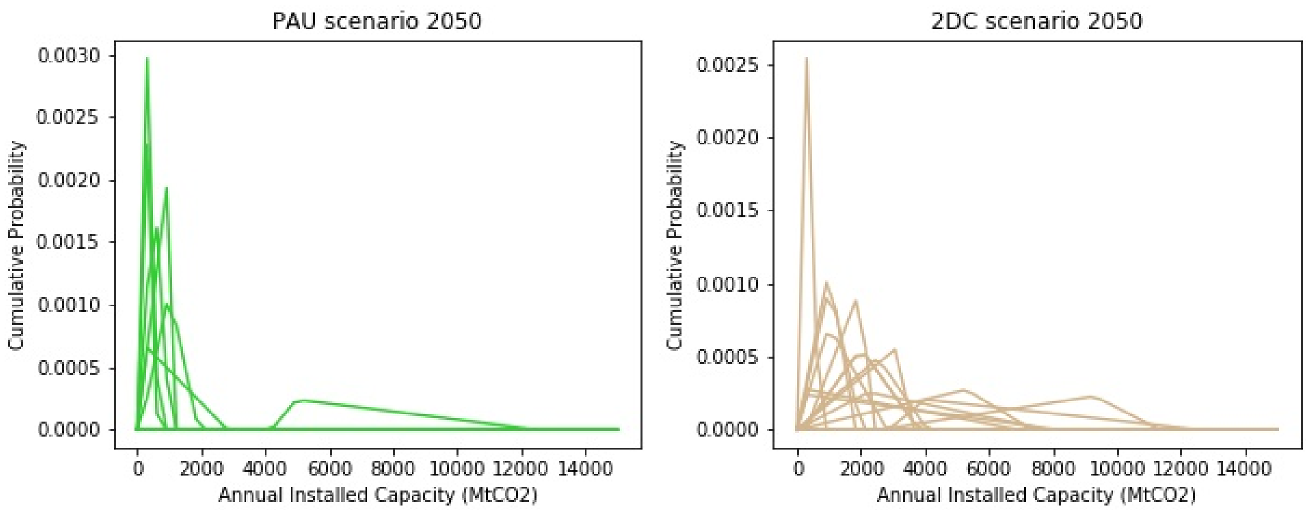

Figure S8. Probability distribution functions (PDF) for annual installed capacity in 2050 for each expert. Probability distributions are triangular fit to 10th, 50th, and 90th percentiles for both solid sorbent and liquid solvent technologies under PAU (green lines) and 2DC (brown lines) scenarios.

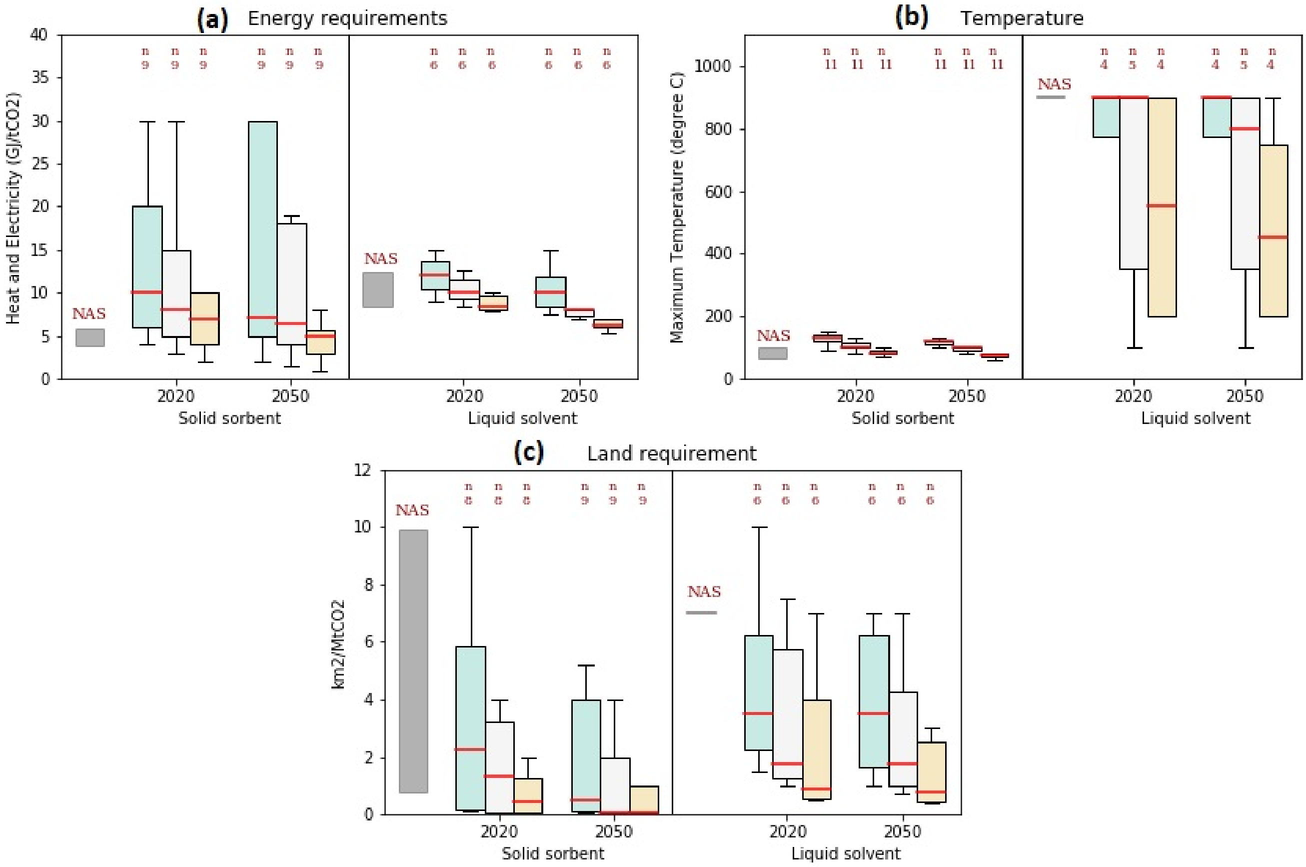

Figure S9. Energy, temperature, and land requirements as the combination of heat and electricity for solid sorbent and liquid solvent technologies under PAU scenario. The results are reported for two years (2020 and 2050). The green, white, and range boxes show the high, median, and low estimates respectively. The box plots show first, second (median), and third quartiles of the distribution. The whiskers indicate the maximum and minimum values. The gray box indicate the range of values reported in the reports by the National Academy of Sciences (National Academies of Sciences Engineering and Medicine, 2019). The numbers at the top indicate the number of recorded responses in each category.

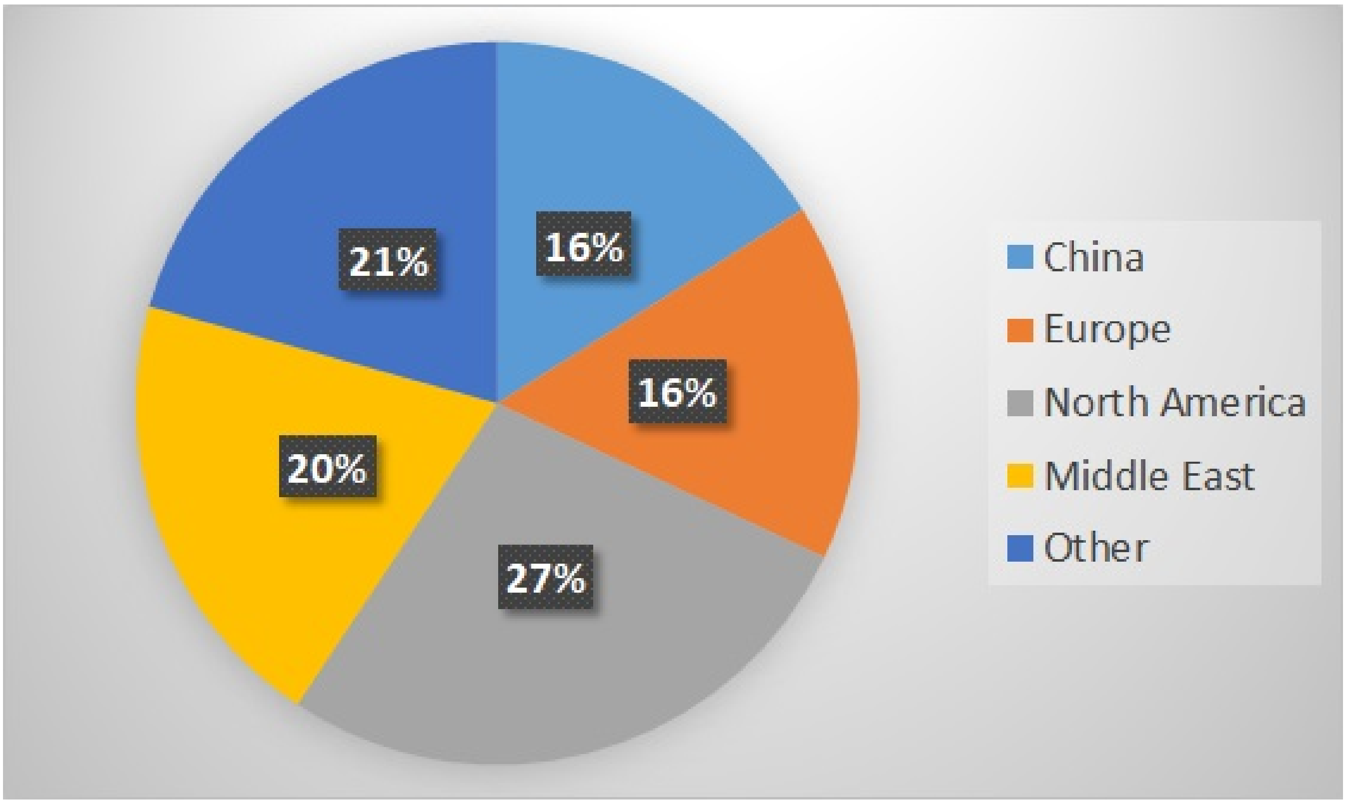

Figure S10. Geographic distribution of DAC plants in 2050

Consent Form

consent 0.

CONSENT FORM

STUDY OVERVIEW The purpose of this study is to investigate how experts see the future of climate related technologies. This study is carried out within the research project RISICO (RISk and uncertainty in developing and Implementing Climate change pOlicies) funded by the European Commission.

RISKS There are no foreseeable risks or discomforts to you in filling out the questionnaire or completing the tasks. The only known risk to you of your involvement in this study is the inconvenience of giving up roughly 30-minutes of your time. All safeguards will be taken to maintain the confidentiality of your data, as described in the "Confidentiality" section below.

BENEFITS There are no direct benefits that will come to you for participating in this survey. However, there are indirect benefits arising from the potential of the survey to provide valuable information about the future of these technologies. Your participation in this survey will, therefore, be of scientific value by contributing to our understanding of the possible solutions to the climate change problem.

CONFIDENTIALITY To ensure confidentiality, data will be collected using Qualtrics and analyzed and stored with code numbers. Data will be kept on secure servers and password-protected computers. The data will be stored after the termination of the current research for a period no shorter than 6 years, and at no time will any identifying information about the participants be stored along with the data. The following people and/or agencies will be able to look at and copy your research records: The investigators, study staff and other professionals who may be evaluating the study.

VOLUNTARY PARTICIPATION Participation in this study is completely voluntary and non-coercive with no negative consequences for refusal to participate. You may choose to leave the study at any point if you experience discomfort or find that there are any parts of this study that you do not wish to complete. Furthermore, you may refuse to participate or withdraw from the study at any time without penalty or loss of benefits to which you are otherwise entitled. Finally, you may refuse to complete any of the questionnaires or refuse to partake in any of the tasks without penalty or negative consequences.

PARTICIPANT'S STATEMENT I have read the study description and I volunteer to take part in this research. If I have questions about the research, I can ask the researcher listed above. I understand that I may refuse to participate or withdraw from participation at any time. I certify that I am 18 years of age or older and freely give my consent to participate in this study.

STUDY DESCRIPTION We are asking you to take part in a research study sponsored by the University of Bocconi under the direction of Professors Valentina. This study is by invitation only. If you have any questions about this research you may contact Valentina Bosetti at the Ettore Bocconi Department of Economics, 20163, Milan, Italy telephone +39 02.5836.2227, email valentina.bosetti@unibocconi.it. This experiment is run under the protocol number 001111929 17/11/2017.

- » Your full name
- » Date

consent 1. Please sign your name and print the date in the space provided below.

Your full name	
Date	

Direct Air Capture
Expert Elicitation Survey

Direct air capture (DAC) is a technology for removing CO2 directly from the atmosphere through the use of capture technologies that bind to CO2. There are currently 3 main companies working on developing this technology in North America and Europe. The two main technologies used for capturing CO2 are based on solid sorbent and liquid solvent materials.

Another closely related technology for removing CO2 is ***Carbon capture, utilization and storage (CCUS)****. This technology can be applied in the industrial sector and in power generation. There are now 43 commercial large-scale global CCUS facilities, 18 in operation, five in construction and 20 in various stages of development.*

There are currently two main subsidy programs in the U.S. to support CCUS/DAC projects:
- *California's Low Carbon Fuel Standard is designed to reduce GHG emissions in the transportation sector by providing a fuel intensity benchmark and creating a market for trading fuel credits.*
- *Amendments to Section 45Q of the Internal Revenue Code (Title 26 of U.S. Code) provide the tax credit for COx used in EOR and sequestered in secure geologic storage or sequestered in a utilization project.*

We will first start with a small number of questions that we will use for calibrating the results of the survey.
For more information about this method, you can watch a 10-min video here: http://www.rff.org/sej

Block 7

Intro. In this part of the survey, we want you to consider **two policy scenarios** and to give us your judgment about the future development of DAC technologies under each scenario.

Cost 2DC

2DC 0.
Please consider a **2-degrees-Celsius (2DC) scenario** where there will be a **coordinated effort by all nations** to reduce the emissions in line with the Paris agreement goal of keeping global temperature rise well below 2 °C. According to the IPCC 1.5SR, this requires achieving **global carbon neutrality by 2050-60**.

2DC 1.
We want you to give us your opinion about only **one of the possible DAC technologies.** Which one do you think will be the dominant DAC technology by **2050** under **2DC scenario**?

- ○ Solid sorbent
- ○ Liquid solvent
- ○ Other technology: ______

2DC 2.
From now on please provide information considering only this technology.

What is the 90% confidence interval of **CAPEX** for your chosen DAC technology under **2DC scenario**? (USD/tCO2 removed)

	2020	2050
Upper limit		
Lower limit		
Median Estimate		

2DC 3.
What is the 90% confidence interval of **OPEX** for your chosen DAC technology under **2DC scenario**? (USD/tCO2 removed)

	2020	2050
Upper limit		
Lower limit		
Median estimate		

2DC 4.
What is the 90% confidence interval of **annual installed capacity** for your chosen DAC technology under **2DC scenario**? (MtCO2/year)
For reference, fossil fuel energy has historically grown at less than 10% per year. Renewable energies such as wind and solar have exceeded 20% per year.

	2020	2050
Upper limit		
Lower limit		
Median Estimate		

Cost PAU

PAU 0.
Please consider a **policy-as-usual (PAU)** scenario where policies are consistent with current efforts and with plans laid out by the **Nationally Determined Contributions.**

PAU 1.
We want you to give us your judgments in relation to only **one of the possible DAC technologies**. Which one do you think will be the dominant DAC technology by **2050** under **PAU scenario**?

- Solid sorbent
- Liquid solvent
- Other technology

PAU 2.
From now on please provide information considering only this technology.

What is the 90% confidence interval of **CAPEX** for this technology under **PAU scenario**? (USD/tCO2 removed)

	2020	2050
Upper limit		

	2020	2050
Lower limit		
Median estimate		

PAU 3.
What is the 90% confidence interval of **OPEX** for this technology under **PAU scenario**? (USD/tCO2 removed)

	2020	2050
Upper limit		
Lower limit		
Median estimate		

PAU 4.
What is the 90% confidence interval of **annual installed capacity** for your chosen DAC technology under **PAU scenario**? (MtCO2/year)
For reference, fossil fuel energy has historically grown at less than 10% per year. Renewable energies such as wind and solar have exceeded 20% per year.

	2020	2050
Upper limit		
Lower limit		
Median estimate		

Energy

Energy 0.
For the rest of the questions in the survey we would like you to focus on **your choice of the dominant DAC technology under PAU scenario**. We refer to this technology as "*the DAC technology*".

Energy 1.
What is the 90% confidence interval of **temperature** requirement for removing one ton of CO2 using the DAC technology? (degreeC)

	2020	2050
Upper limit		
Lower Limit		
Median estimate		

Energy 2.
What is the 90% confidence interval of **energy (heat + electricity)** requirement for removing one ton of CO2 using the DAC technology? (GJ/tCO2)

	2020	2050
Upper limit		
Lower Limit		
Median estimate		

Energy 3.
What is the 90% confidence interval of **land requirement** for removing one ton of CO_2 per year using the DAC technology? ($m^2/MtCO_2$ per year)

	2020	2050
Upper limit		
Lower limit		
Median estimate		

Energy 4. What will be the most likely **renewable source of electricity** for the DAC technology in **2050**?

- ☐ Solar
- ☐ Wind
- ☐ Geothermal
- ☐ Biomass
- ☐ Nuclear
- ☐ Other

Operation

Operation 1.
What is the 90% confidence interval of **uptime (percentage of time that a plant with the DAC technology will be working and available)**? (%)

	2020	2050
Upper limit		
Lower limit		
Median estimate		

Operation 2.
What is the 90% confidence interval of **lifespan** of a typical plant with the DAC technology? (number of years)

	2020	2050
Upper limit		
Lower limit		
Median estimate		

Operation 3.
What is the 90% confidence interval of the **commercial size (capacity)** of a plant with the DAC technology? ($MtCO_2$/year)

	2020	2050
Upper limit		

	2020	2050
Lower limit		
Median estimate		

Utilization

Util 1. How would you rank the **carbon storage/utilization options** that will be using CO2 from the plants with the DAC technology by **2050** in terms of their capacity?

- Geological storage
- Enhanced oil recovery (EOR)
- Air-to-fuel
- Beverage industry
- Other

Util 2. What do you think will be the **most critical limiting factor(s)** for large scale (i.e. Gt scale) deployment of DAC in **2050**?

- Storage capacity
- Energy use
- Land
- Chemical sorbents
- Carbon cycle feedback
- Social acceptability
- Policy and regulations
- Other

Util 3. How would you rank the **most likely facilities** that will be in close vicinity of a DAC plant in **2050**?

- Solar/wind farm
- Geothermal reservoir
- Fossil fuel power plant
- Oil extraction plant
- Nuclear power plant
- Other

Util 4. What percentage of the total installed capacity of the plants with the DAC technology in **2050** will be in the following **locations** ? (please be sure the column sums to 100%)

	Share of total installed capacity
China	0
Europe	0
Middle East	0
North America	0
Rest of the World	0
Other	0
#Conjoint, Total#	0

Util 5.
What is the 90% confidence interval of the **optimal size (capacity)** of a plant with the DAC technology that the government can support as a **pilot project in short term**? (tCO2/year)

- 10
- 100
- 1000
- Other

Util 6. How would you rank the **policies** that will support DAC projects by 2050?

- Carbon credit market (e.g. LCFS)
- Carbon tax
- R&D subsidies
- Carbon mandate
- Other

End

Experts.
Would you like to suggest name to be included in this survey?