Identifying regionally dependent barriers in the Carbon Capture and Storage industry

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Carbon capture and storage (CCS) has long been cited as an integral part of deep decarbonisation pathways for the global economy, given its ability to curtail point-source emissions from power plants and industrial facilities that utilise fossil fuels. However, development and deployment has failed to meet expectations due to a range of techno-economic and socio-political barriers. While prior literature typically focusses on understanding perceptions across select regions, we aimed to identify both universal and regionally dependent barriers to deployment by distributing a survey to CCS professionals around the world. We found firstly that respondents had extremely pessimistic expectations on the ability for CCS to meet capacity targets required for deep decarbonisation in scenarios such as the 2°C scenario from the International Energy Agency. On average, socio-political factors were perceived as the highest barrier towards deployment, whilst technical and economic factors had a wide variance in perception. There was widespread agreement on several barriers to CCS deployment irrespective of region, such as infrastructure development and public awareness, signifying major hurdles that the global CCS industry must address as a whole in order to promote widespread deployment. Other variables, such as general public support and the strength of activism, revealed a strong regional dependency, with respondents from the Middle East and China generally more optimistic than those from North America and Oceania/S & SE Asia. While regional variation might suggest the potential for international learning, many of these regional dependencies are linked to largely immutable factors, such as political structures and geography. Hence, the prospects for international learning through information sharing may be limited in practice.

Keywords: Carbon capture and storage, survey, decarbonisation, barriers

1 Introduction

The growing commitment of governments around the world to reduce CO_2 emissions and prevent excessive global warming has drawn further attention to the merits of carbon capture and storage (CCS) technologies. CCS involves separating, capturing, and compressing CO_2 emitted from point sources such as conventional power plants or industrial processes, then transporting and injecting it in deep geological formations including, but not limited to, saline aquifers and depleted hydrocarbon reservoirs. In this regard, CCS provides the potential for CO_2 emissions reductions that would enable the continued utilisation of fossil fuel resources, a feature that draws significant criticism from environmental groups.

Coupled with biomass utilisation, bioenergy with CCS (BECCS) has also been identified as having the potential to achieve net negative emissions. Numerous studies and reports have stressed the importance of such negative emissions technologies being widespread after 2050 to achieve the required deep decarbonisation targets [1–5]. Indeed, the Intergovernmental Panel on Climate Change (IPCC) in their fifth assessment report (AR5) include some form of carbon capture technology for the majority of their scenarios for to remain below a 2°C increase from pre-industrial levels [6]. Furthermore, whilst acknowledging uncertainties, many experts have expressed optimism about the viability and potential of the technology and its widespread deployment [7–9]. However, despite this perceived importance, the number of large-scale integrated projects has fallen well short of ambitions held by government and industry [10]. This paper explores the reasons that this technology, widely considered critical for deep decarbonisation, has yet to attract sustained support or investment.

Extensive literature has been published thus far investigating the uncertainties and acceptance of CCS. These studies have taken either a focus on the socio-political aspects [11–16], the techno-economic aspects [4,10,17–21] or, less extensively, both in tandem [8,22,23]. Garnett et al., 2014 further explored the barriers to major investment in CCS, citing the scale and complexity of projects and the lengthy, at-risk, front-end development required, coupled with the lack of a commercial rationale as the core reasons for stalled investments. Despite the global importance of CCS, much of the literature has focussed on one region and or usually surveyed only one category of stakeholder, with only some studies conducted across different regions [24–26]. Although these studies largely arrive at similar conclusions as to the uncertainties facing CCS deployment, we cannot easily determine whether the uncertainties are globally consistent or specific to the region being surveyed. This paper addresses that gap by probing the differences between regions, and examining the vulnerabilities of CCS in finer detail.

Through a survey distributed to a range of CCS professionals around the world, we aim to gain a perspective on the current state of several techno-economic (e.g. system costs, infrastructure requirements, technological maturity) and socio-political (e.g. local public support, prevalence of activism, public awareness) variables for each region. The objective was not only to better understand the key vulnerabilities for CCS that are common across all regions, but also identify how these barriers might vary regionally. This analysis can provide insight into the nature of the barriers restricting deployment of CCS, and evaluate the potential for technology transfer, local policy initiatives, and international learning to improve deployment prospects.

2 Methodology

2.1 Survey method

The elicitation process involved identifying a diverse collection of people working in a field related to CCS and surveying their perceptions on various techno-economic and socio-political variables identified in existing literature. International CCS professionals with a variety of roles and disciplinary backgrounds were identified through personal contacts and key personnel involved in previously delivered projects. Their positions ranged from academia to practitioners. Respondents were invited to complete the survey via an online link emailed to them, and were also asked to forward the link to those they considered relevant people in order to increase the potential respondents. The use of an online survey was chosen primarily due to its ease of distribution to a worldwide audience, providing access to a unique population that would otherwise be difficult to reach. However, this research tool typically comes with some disadvantages, primarily relying on information provided by the interviewee to gather demographics, and a lack of control over distribution through forwarded links [27]. In order to alleviate some of these issues, preliminary demographic questions were asked in order to gauge background data on the respondents. This included:

(i) region of expertise;

(ii) years of experience in CCS;

(iii) nature of experience in CCS; and

(iv) self-rated knowledge.

Self-rated knowledge was determined by asking respondents to rate their knowledge in several fields related to CCS (e.g. capture, transport, policy, project management, etc.) on a Likert scale (1 – No Knowledge, 5 – Expert Knowledge). Respondents were made aware of the purposes of the survey through its introduction, and were not compensated for their time. Despite the global focus, the survey was not translated from English into other languages. While we attempted to survey a sufficient number of professionals from various regions, we cannot claim a representative sample.

2.2 Participants

Responses from the survey were collected from a total of 51 respondents in 5 separate regions over a four-week period from the 13th of February to the 13th of March, 2017. This number was reduced to 42 when accounting for participants who answered less than 10% of the survey. An initial direct elicitation of 91 links were sent, but as participants were given the option of forwarding the survey to others, the total number who gained access to the survey may have been greater than this. Respondents took an average of 23.5 minutes to complete the survey. There was no obligation to complete all questions presented.

Table 1 lists the regional distribution of respondents, that is, the region about which they indicated their CCS knowledge primarily applies (not necessarily where they live or work).

Table 1: Distribution of reported regional expertise by survey respondents

Region	Respondents
Oceania/S & SE Asia (incl. India, Australia, and New Zealand)	21
China	2
Europe (incl. UK and Russia)	7
Middle East	3
North America (incl. Mexico and Canada)	9
South America	0
Africa	0
Total	42

Half of our respondents were from the Oceania/S & SE Asia (50%) region due in part to this being the region of origin of the study. North America (21%) and Europe (17%) also made up considerable portions of respondents, while the remainder were from the Middle East (7.1%) and China (4.8%). Although contacted, no responses were obtained from South America or Africa. . Our respondents indicated a range of experience, with most reporting they had 10 – 15 (38%), 5 – 10 (31%), or 15+ (19%) years in a field related to CCS. The remainder had2 – 5 (9.5%) years of experience, with only one reporting less than two (2.4%). Additionally, the background of respondents was split fairly evenly amongst academia (26%), engineering (29%), policy planning (19%), and project management (26%).

Finally, self-rated knowledge indicated on average that our CCS professionals ranged between Informed (3) and High Knowledge (4), with particular strength in the field of research and development (see Fig. 1).

Figure 1: Average self-rated knowledge of respondents in several fields of CCS expertise. 1 - "No Knowledge"; 2 – "Some Knowledge"; 3 – "Informed"; 4 – "High Knowledge"; 5 – "Expert Knowledge".

2.3 Survey protocol

Survey questions pertained to commonly identified barriers in literature regarding CCS, and respondents were asked to answer the questions with their particular region of expertise in mind. Firstly however, respondents were asked about their optimism regarding the role of CCS in decarbonisation scenarios. To do this, we provided information concerning the current deployment rate of CCS compared to the requirements set out by the IEA 2DS [5]. The IEA 2DS outlines a pathway to a low-carbon economy by 2050 that aligns with the objective of limiting global warming to 2°C, in effect meeting the minimum goals of the recent Paris Agreement [28]. Included within this pathway is a scenario for CCS deployment shown in Figure 2, requiring an increase of two orders of magnitude from the current capture capacity of 40 Mtpa to 4,000 Mtpa by 2040 [29]. To ascertain optimism, we asked for their view as to the feasibility of reaching these targets on a 5-point Likert scale (1 – Very Low, 5 – Very High).

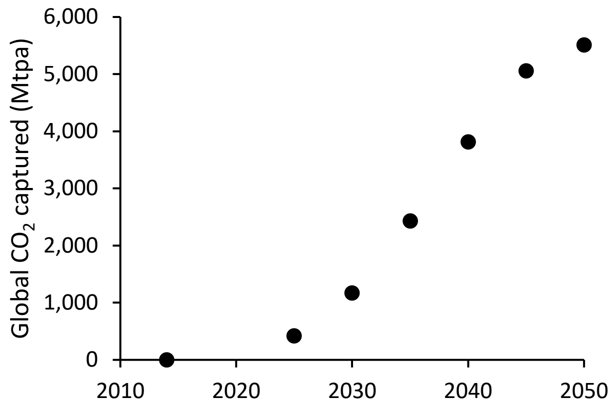


Figure 2: IEA 2DS scenario pathway for global CO_2 capture up to 2050 [5].

After this initial question, 36 questions were asked (excluding aforementioned demographic questions),split into four categories – technical, economic, social, and political.

(i) Technical

We addressed technical issues through a range of questions targeting various facets of CCS. We assessed the perceived probability of meeting CCS projections for deep decarbonisation, as well as the current and perceived maximum deployment rates. Technological maturity was also assessed on a Technological Readiness Level (TRL) scale from 1-9 and a Commercial Readiness Level (CRL) scale from 1-6 [30]. To assess transport, respondents were asked the average distances from point source to basin for their region as a whole. For storage, respondents were asked about the number and capacity of basins, and for long-term average injectivity of the region, respondents were asked 'What is the average injectivity of the prospective sedimentary basins in your region (Mtpa/well)?', with a range from 0 - 5. Finally, the level of additional infrastructure required in each region was also assessed with the following question: 'How much of the infrastructure required to reach your region's maximum potential for CCS is already operational?', where respondents could answer within fiveintervals intervals from 0 – 100%.

(ii) Economic

Primarily, we assessed economic variables pertaining to capture, transport, and storage. For example, to judge capture costs, respondents were asked to answer: ‘On average, what are the costs for CO_2 capture per tonne in your region? (US$/tonne)’, with five intervals between 0 – 100. In a similar fashion, respondents were asked about transport and storage costs for their given region. We also ascertained the level of government incentives in the region using a 5-point Likert scale (1 – Very Low, 5 – Very High) with the questions: ‘How would you rate the dollar amount of government incentives to CCS deployment in your region?’; and ‘How would you rate the certainty/stability of these incentives in your region?’. Additionally, respondents were asked to rate their perception of the overall cost competitiveness of CCS compared to the attractiveness of alternative low-carbon technologies on a 5-point Likert scale (1 – Very Low, 5 – Very High). In order to assess the effect of incentives, we also asked: ‘Now consider that CCS is given the same fiscal incentives per tonne abated that other technologies like wind and solar receive in your region. How does that change the answer that you gave in the previous question?’.

(iii) Social

All social variables used a 5-point Likert scale (1 – Very Low, 5 – Very High) to ascertain the respondents’ perceptions of the public’s views on a wide range of variables, including cultural significance of the land, local and general perceived risks, environmental benefits, as well as their perception of the public’s knowledge. We also asked respondents to rate how they believe local communities in their region perceive CCS, on issues such as landholder compensation, consultative processes, and previous experience with large industry projects. Other questions included asking how respondents would rate: ‘the public support for CCS (or related industries) in communities neighbouring storage sites in your region?’, ‘the general public’s support for CCS as a technology in your region’, ‘the general public support for alternative carbon mitigation techniques in the region’, and ‘the general public’s views on urgency for climate change action’.

(iv) Political

Only a few, select questions were asked about political factors in the CCS industry. These pertained to land use competition, planning efficacy (perceived public influence over planning approvals), and CCS deployment targets set by the regions’ governments. We classified land use competition as a political barrier since there are extensive uncertainties surrounding property rights and access to land used for alternative purposes, all of which fall under a political and legislative category. The regulatory environment was also assessed by asking ‘How would you rate the level of clear policy-driven regulatory frameworks for CCS in your region?’. As with the social factors, all questions were assessed on a 5-point Likert scale (1 – Very Low, 5 – Very High) to ascertain perceptions of each issue. Finally, we assessed the overall likelihood of planning approval success on a scale from 0 – 100% for CCS projects in the region.

(v) Summary

The response ranges for each surveyed variable are provided in Table 2, noting that the overarching range of 1 to 5 indicates which responses indicated a very high or very low barrier respectively. Notably, most responses were recorded on a 5-point Likert scale. The number of respondents who answered each question (out of the 42 elicited) is also provided.

Table 2: List of all surveyed variables with the corresponding response options. The guide from 1 to 5 indicates whether that response is a high or low barrier to CCS deployment respectively.

Variable	Response range					*n*
Technical	***1 (-)***	***2***	***3***	***4***	***5 (+)***	
Maximum Deployment Rate (Mtpa/yr)	0 – 2.5	2.5 – 5	5 – 12.5	12.5 – 25	25+	37
Current Deployment Rate (Mtpa/yr)	0 – 0.25	0.25 – 0.5	0.5 – 1.25	1.25 – 2.5	2.5+	40
Existing Infrastructure (%)	0 – 20	20 – 40	40 – 60	60 – 80	80 – 100	37
Injectivity per well (Mtpa/well)	0 – 0.1	0.1 – 0.5	0.5 - 1	1 – 5	5+	25
Basin Capacity (Mtpa)	0 – 10	10 - 50	50 - 100	100 – 200	200+	32
Technology Readiness Level (CRL)	1 (0) – 3 (0)	4 (0) – 6 (0)	7 (0) – 9 (2)	9 (3) – 9 (4)	9 (5) – 9 (6)	40
Distance to Storage (km)	1000 – 2000	500 – 1000	200 – 500	50 – 200	0 – 50	31
Geological Stability	Very Low	Low	Average	High	Very High	40
Economic	***1***	***2***	***3***	***4***	***5***	
Cost Competitiveness	Very Low	Low	Average	High	Very High	39
Cost Competitiveness w/ Incentives	Very Low	Low	Average	High	Very High	36
Affordability of Fossil Fuels	Very Low	Low	Average	High	Very High	41
International Economic Environment	Very Low	Low	Average	High	Very High	40
Incentive Amount	Very Low	Low	Average	High	Very High	40
Incentive Stability	Very Low	Low	Average	High	Very High	40
Cost of Storage (USD/tonne)	20+	10 – 20	5 – 10	2 – 5	0 - 2	33
Cost of Transport (USD/tonne)	20+	10 – 20	5 – 10	2 – 5	0 - 2	22
Cost of Capture (USD/tonne)	80 – 100	60 – 80	40 – 60	20 – 40	0 – 20	33
Social	***1***	***2***	***3***	***4***	***5***	
General Perceived Risk	Very High	High	Average	Low	Very Low	40
Public Knowledge	Very Low	Low	Average	High	Very High	40
Local Perceived Risk	Very High	High	Average	Low	Very Low	40
Cultural Significance of Land	Very High	High	Average	Low	Very Low	39
Activist Groups	Very High	High	Average	Low	Very Low	39
Public Consultation	Very Low	Low	Average	High	Very High	36
Landholder Compensation	Very Low	Low	Average	High	Very High	37
Local Public Support	Very Low	Low	Average	High	Very High	36
Previous Exposure to Industry	Very Low	Low	Average	High	Very High	36
Perceived Environmental Benefits	Very Low	Low	Average	High	Very High	40
Public Climate Urgency	Very Low	Low	Average	High	Very High	40
Support for Alternatives	Very High	High	Average	Low	Very Low	40
General Public Support	Very Low	Low	Average	High	Very High	40
Political	***1***	***2***	***3***	***4***	***5***	
Planning Efficacy	Very Low	Low	Average	High	Very High	39
Land Use Competition	Very High	High	Average	Low	Very Low	39
Planning Approval Likelihood (%)	0 – 20	20 – 40	40 – 60	60 – 80	80 – 100	40
Regulatory Framework	Very Low	Low	Average	High	Very High	40
CCS Deployment Targets	Very Low	Low	Average	High	Very High	38
Energy Demand and Growth	Very Low	Low	Average	High	Very High	40

3 Results

3.1 Examining optimism about CCS

Optimism surrounding the future and value of CCS technology amongst experts has typically been high in prior studies, predominately attributed to bias and confidence in eventual scalability [7,8], as well as techno-optimism for new innovation [31]. This is despite a view that combining several major industries along a complex value-chain amplifies uncertainty and risk [20] and potentially creates significant organisational difficulties aligning goals between parties with varying risk appetites [8,10].

Based on our question regarding the feasibility of reaching the targets for CCS outlined in the IEA 2DS, respondents were overwhelmingly negative, with about 87% responding that the probability was either "Low" or "Very Low", and none indicating a "Very High" probability. This indicates a strong level of uncertainty surrounding the role of CCS in future decarbonisation scenarios, and contradicts prior studies where confidence was high amongst those working in the CCS industry [7,8]. Given one of these studies is very recent, this may rule out evolving views on the industry. Instead, we expect the discrepancy is because our study poses the question in the context of data outlining the magnitude of the challenge. When framed as such, this may have lead our respondents to re-evaluate their former optimism.

3.2 Overall assessment of category responses

To better understand perceptions of the CCS industry, we averaged the scores for each primary category of question (technical, economic, social, and political). As noted in Fig. 3, all category means fell below 3, with a one-sample one-sided t-test indicating the statistical significance of this deviation (p<0.05). As such, all four categories exhibit some degree of pessimism. Clarifying the differences between the categories through two-sample one-sided t-tests (unpooled variance) on each pair, we find that the Social category, with a mean of 2.53, is significantly lower than the other three means (p<0.05), all of which are statistically similar. Thus, while on average our respondents exhibit a similar degree of mild pessimism regarding technical, economic, social, and political factors regarding CCS, this pessimism is significantly larger for social variables.

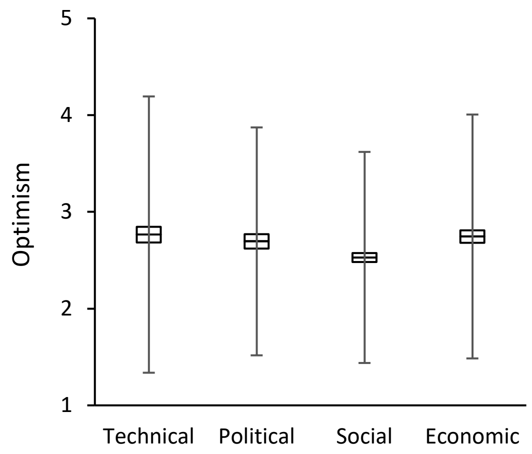


Figure 3: Average response for each of the four primary categories of question – technical, economic, social, and political. A lower response score corresponds to the issue being regarded as more of a barrier for CCS, with 3 as a neutral response. The box indicates the standard error about the mean, whilst the bars indicate a standard deviation either way from the mean.

3.3 Understanding regional perceptions and variability

Breaking down the responses to each question based on the region of expertise, we find that some perceptions are universally agreed-upon, whilst others have significant regional dependencies. Figure 4 provides an outline of the average responses for each surveyed variable broken into separate regions, with the average across all regions also provided.

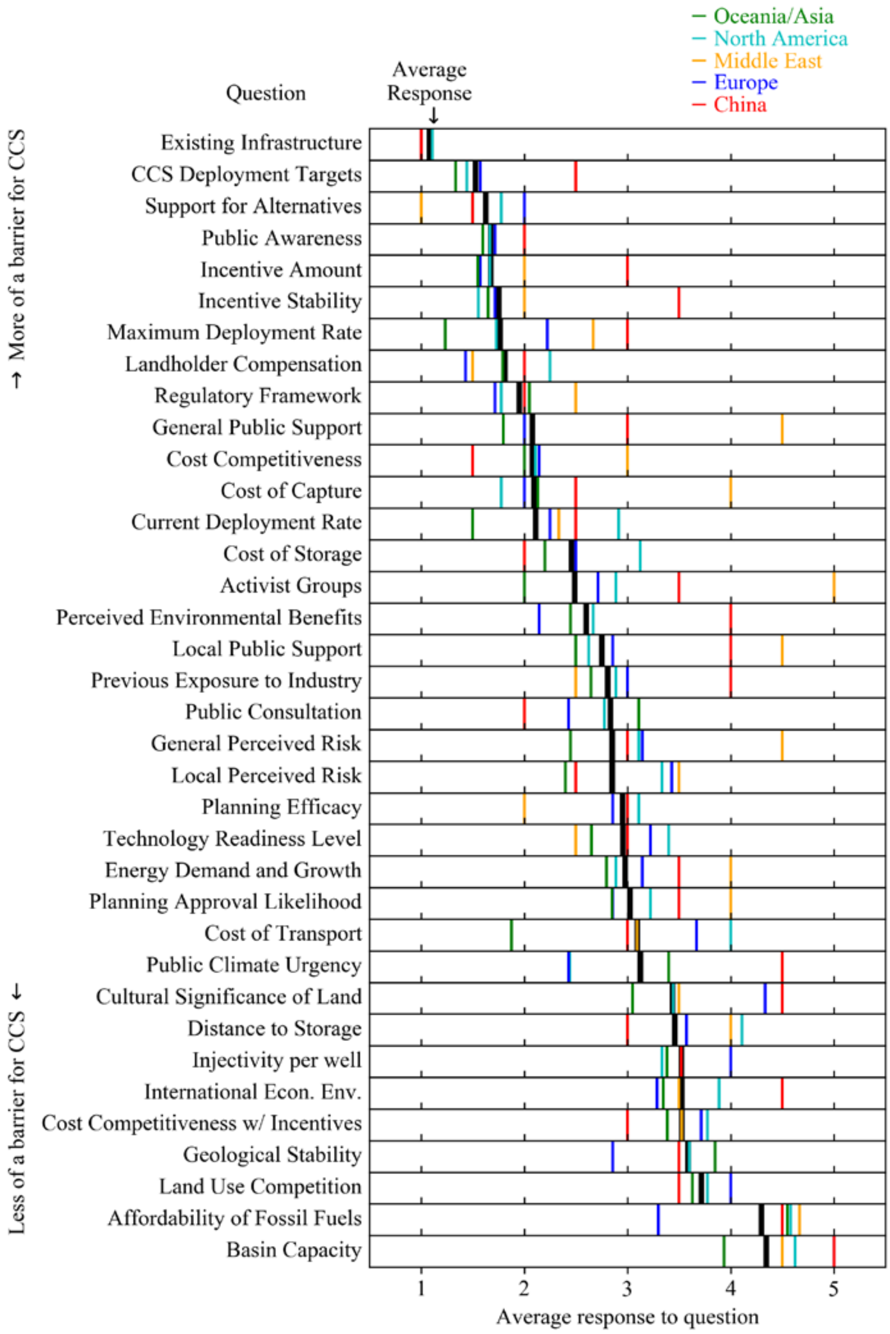
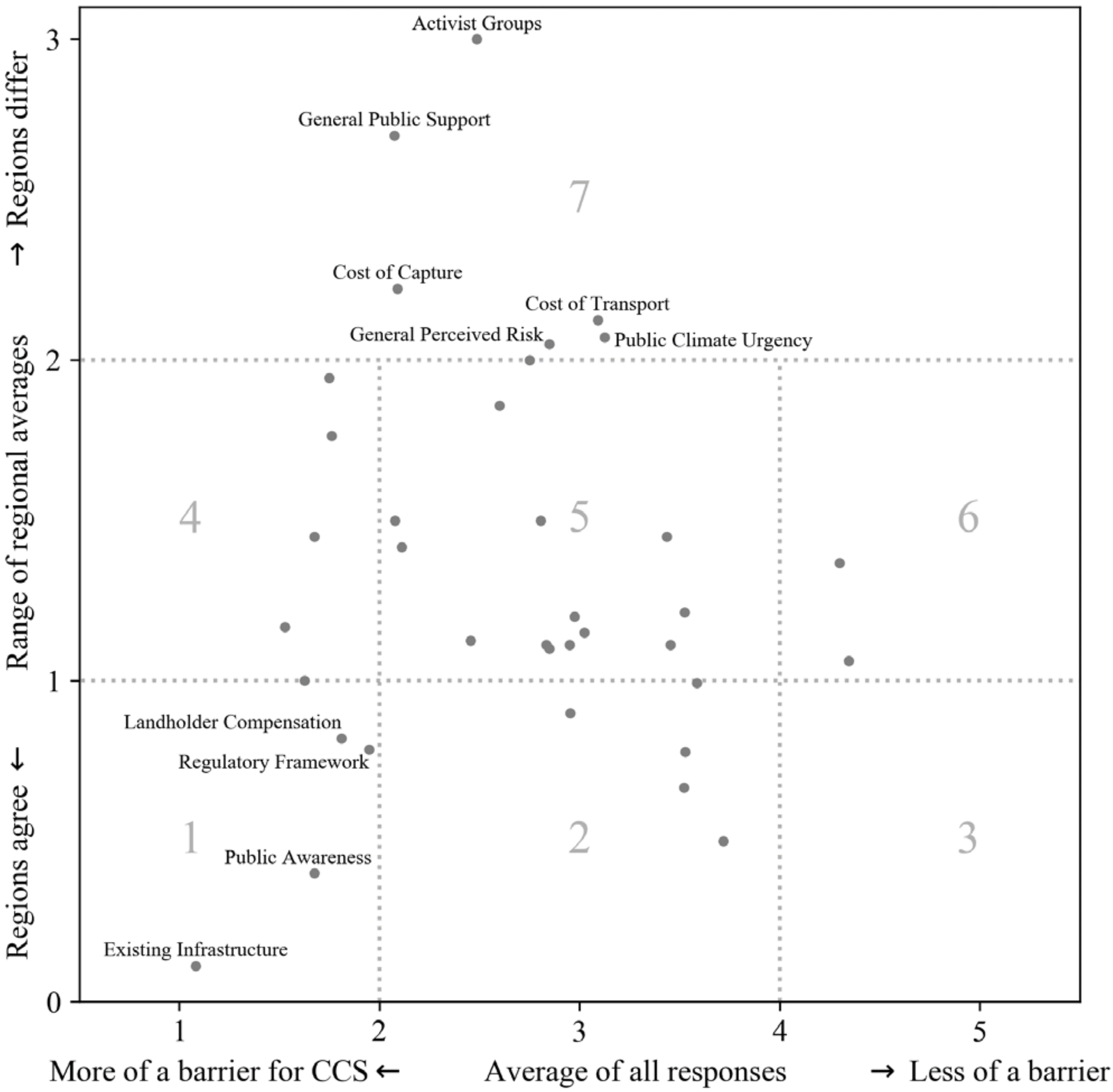


Figure 4: (COLOR) List of all survey responses. The mean response from each region is provided for each question, with the black line indicating the average across all regions. The variables are ordered such that the lowest mean (and thus the highest barrier) is at the top of the list.

To further examine the regional variability between respondents, we show the distribution of variables on two axes (Fig. 5). The horizontal axis is the global average response across all regions (i.e. the black line in Fig. 4), with 1 indicating a high barrier and 5 indicating a low barrier to CCS implementation. The vertical axis is the regional variability, measured through taking the difference between the highest and lowest regional mean for a given variable. This parameter space can be divided into seven areas of interest, and we will briefly examine each of these before focusing in on two of particular interest. The first of these two is Sector 1, denoting variables which all respondents scored as low regardless of their region of expertise, signifying that these factors may present universally agreed-upon barriers to the deployment of CCS.

Second, we will examine Sector 7, factors which exhibit high regional variability[1]. These will indicate variables where certain regions are more favourable than others, perhaps indicating opportunities for international learning. Additionally, this may provide insight into regions where optimism towards CCS is either particularly high or low, which may influence the capacity of these regions to rapidly scale their respective industries.



[1] The variables with the highest regional variability are left within one larger category (Sector 7), since a high regional variability (i.e. at least one region with a high score and at least one region with a low score) dictates that the global average (horizontal axis) will tend toward the middle (~3). As such differences between the mean scores of variables are less informative when there is high variability in response.

Figure 5: Relationship between perception and regional divergence for each identified variable. For clarity, labels are only provided for variables in Sector 1 and Sector 7 as these are discussed in-depth given their significance. Refer to Fig. 4 for a full list of variables.

(i) Sector 1 – Common barriers

Sector 1 identifies variables which CCS professionals from all regions perceived as barriers. These are challenges which likely require global interventions to overcome, as they present as problems in all surveyed regions and may signify key weaknesses in the scalability of the CCS industry. The strongest barrier identified was the level of existing infrastructure with reference to what is required to meet regional potential for CCS, where 93.8% of respondents gave the response of 'Very Low'. This barrier was accompanied by a similarly pessimistic view on public awareness, clarity of regulatory framework, and landholder compensation for neighbouring communities affected by CCS operations, all of which were perceived as universally negative.

(ii) Sector 2 – Common neutrals

This sector of common neutrals describes factors in which all respondents, agreed there was no strong positive or negative perception either way. While there is room for improvement through global initiatives and learning, these variables are not perceived to pose a direct barrier towards the expansion of the industry and therefore require less attention. Included within this sector is the level of local land use competition, injectivity per well, cost competitiveness with incentives in place, geological stability, and technological maturity. Cost competitiveness with incentives is interesting, as it means that all of our respondents would consider CCS on a similar standing with alternative technologies if equivalent incentives were in place. This is in contrast to much more regional divergence when subsidies are not in place.

(iii) Sector 3 – Common enablers

This sector describes variables which professionals in all regions perceived as positive in enabling CCS deployment. Interestingly, this sector contains no variables from our survey, indicating that that no factor was universally agreed-upon as positive across all regions. This result tells us one of two things. Either there were not enough questions asked of respondents that could be perceived positively, or potentially there are no variables about the CCS industry that are positive in all regions. This is consistent with the pessimism amongst our respondents exhibited earlier, and is of concern when considering the role of CCS in future decarbonisation scenarios..

(iv) Sector 4 – Diverging barriers

Sector 4 describes variables that were perceived on average as a barrier, and exhibit a moderate amount of variability between regions of expertise. Variables within this space included support for alternative carbon mitigation techniques, regional CCS deployment targets, and incentive amount/stability. Given all of these are largely dependent on region (e.g. regional deployment targets), this variability is expected.

Additionally, the perceived maximum deployment rate of CCS also fell within this sector, again suggesting a pessimistic, albeit varied, view towards the likelihood of significant CCS deployment.

(v) Sector 5 – Diverging neutrals

This region outlines variables that our respondents perceived as neutral in status and exhibiting only a moderate amount of regional variability. This is where the bulk of identified variables lie, suggesting that most factors in the CCS industry are centred around an average scoring with slight differences in regional opinion. This may be due to ambivalence regarding these factors, or it may also indicate a tendency for respondents to answer on the fence for variables they are uncertain about (although we afforded respondents the option of a 'Don't Know' response). Several variables concerned with public perception of CCS were contained within this space, such as planning efficacy, public consultative processes, the cultural value of the land on which CCS is located, previous exposure of communities to industrial projects, the perceived local risk, and the overall likelihood of planning approval being granted. Local public support and perceived environmental benefits also fell within this space, although with a much higher regional variability than the other variables. This clearly indicates that the perception of local risk is much more universally agreed-upon than the perception of benefits. Other techno-economic factors were included within this space, such as the cost of CO_2 storage, distance to storage, international economic environment, regional energy demand, and overall current deployment rate. Here we also find the current cost competitiveness, with a much higher regional variability than the aforementioned incentives-adjusted competitiveness in Sector 2.

(vi) Sector 6 – Diverging enablers

This space describes variables which are generally perceived in a positive manner towards enabling CCS deployment, but with some regional variation between respondents. Similarly to global enablers, this section is also underpopulated, signifying a lack of optimism amongst respondents. Affordability of fossil fuels and storage basin capacity both fell within this category. While a positive affordability of fuel with some regional dependency is unsurprising, the generally positive perception of basin capacity is an interesting result, given that the availability of storage sites has been a point of concern in previous literature [10].

(vii) Sector 7 – Strong regional dependencies

Finally, Sector 7 describes variables where there was a high amount of regional variability among respondents. That is, the difference between the lowest regional mean and the highest regional mean was above 2 (on a 5-point Likert scale). These variables are important to understand divergent views about the CCS industry, potentially shedding light on pathways towards international learning or priorities for action. The cost of capture and transport both fall within this space, indicating regional dependencies for costs that were not evident with storage. The general public perception of risk is also within this sector, an interesting result considering that local risk was much more agreed upon. This perhaps suggests a disconnect in some regions between how the local community and general public view the technology. The public's view on climate mitigation and their urgency for action also exhibited regional variance, along with the general public support for CCS. Finally, the presence and perceived strength of anti-CCS activism exhibited the highest regional dependency of the survey, indicating a strong variation across the surveyed regions.

4 Discussion

4.1 Examining common barriers

Our survey pool of CCS professionals from around the world agreed on several variables as unfavourable for the industry, as depicted in Sector 1 in Fig. 5. The fact that all regions experience these similar problems in their respective CCS industries suggests that these constitute some of the key barriers or uncertainties facing the industry, ones that may not have easily implementable solutions. Hence, alleviation or clarification of these factors on a worldwide scale is of high priority for the widespread deployment of CCS.

(i) Existing Infrastructure

First and foremost, the existing infrastructure in the region consistently had the lowest perception amongst our respondents. The CCS industry faces barriers in its ability to quickly expand industrial capacity and infrastructure across the supply chain given the relatively limited number of current projects and practical experience [23], and decarbonisation projections may be prematurely expecting rapid unit scaling [32]. Scalability of transport networks is a point of concern, as large-scale utilisation of CCS will require an extensive network of integrated CO_2 pipelines [18,21]. This contributes to an industrial stalemate: it is not worth building a pipeline network without a significant amount of CO_2 captured, but it is difficult to implement a CCS project without the pipeline network in place [21]. These uncertainties surrounding infrastructure were apparent among respondents, almost all of whom agreed that less than 10% of the necessary infrastructure was in place in their respective region.

(ii) Public Awareness

There is an historically low level of public awareness regarding CCS and its functionality, presented over a decade of studies [12–14,33]. Although higher awareness of a given technology is typically indicative of stronger support [34], this notion has been largely debunked in the CCS literature – provision of information has often led to increased opposition and risk perception [35,36]. That being said, Oltra et al. [37] found that presenting the public with analogues to natural CO_2 processes increased support for CCS, and Ashworth et al. [38] found that early engagement could lead to a more positive perception, although the most effective style of communication is debatable [39]. Globally, professionals from all surveyed regions in our study expressed similar concerns regarding the public knowledge around CCS, with an average scoring of less than two on a 5-point Likert scale (1 – Very Low, 5 – Very High). The small size of the global CCS industry, which has not yet progressed anywhere close to the rate required for deep decarbonisation, has also limited public exposure to the technology, and is a key factor driving the universal nature of the problem.

(iii) Regulatory Framework

Our respondents also rated the clarity of regulatory frameworks surrounding CCS poorly for all regions. This is unsurprising, as clear regulation surrounding CCS is widely cited as a leading issue for the industry [4,19,20,23,40], and projects are expected to require extensive legal and regulatory reviews given the emerging nature of GHG legislation [10]. Currently, there exist several detailed legal challenges, particularly around the issues of storage classification, liability, and monitoring responsibility [4,19,41]. Additionally, given the complex value-chain, regulations are often fragmented across several bodies [4,20], including protections to groundwater contamination [40,41] and property rights [42–44]. Mandating the use of CCS through a “capture ready” standard [4] could encourage quicker diffusion of the technology and accelerate the pace of legal frameworks, however this avenue runs the risk of mandating a currently uneconomical technology, discouraging investment [23,45]. Whilst the state of affairs may have improved over the past decade [15], global regulatory frameworks for CCS still require much-needed elaboration and specificity.

(iv) Landholder Compensation

Subsurface property rights related to CO_2 storage have in the past concerned the right to compensation for a landowner above a prospective subsurface formation [43]. In the US, public property rights and compensation currently helps to facilitate the expansion of the CCS industry [42]. This practice is common in natural gas storage rights, where compensation is provided to both the surface owner and mineral owner respectively [42]. However, in other regions such as Australia, ownership of geological storage formations lies with the state, meaning less compensation for landholders [46] and hence less incentive for cooperation. Similar concerns over land rights and permissions have been expressed with regards to CCS storage in other regions around the world, such as the EU [47]. From our survey, there was a consensus that financial compensation available to communities neighbouring storage sites was low, perhaps a result of the lack of clarity regarding the legal precedent for it. We found that respondents from North America indicated a slightly higher prevalence of compensation compared to other regions, possibly due to private ownership of subsurface property as well as the extensive number of legal cases and proceedings that have arisen from similar issues. This includes cases such as *FPL Farming, Ltd. v. Texas Natural Resources Conservation Commission* in Texas, and *United States v. 43.42 Acres of Land* in Louisiana [44].

4.2 Strong regional dependencies

There were several questions where respondents from different regions had significant variation, as identified by Sector 7 in Fig. 5. We find the regional distribution of these variables laid out in Fig. 6. The use of technology transfer within the CCS industry could accelerate the progression of the industry [48], and indeed the presence of regionally dependent variables in our study suggests room for international learning. However, these mechanisms are often difficult due to organisational differences and varying political wills [49], along with a lack of commercial value proposition and the complexity of the technology [8]. Indeed, variation may be due to uncontrollable factors such as geographical constraints, geological limitations, or political structures, suggesting that regional differentiation may not be easily alleviated. We will therefore examine the potential for transferability individually for each variable.

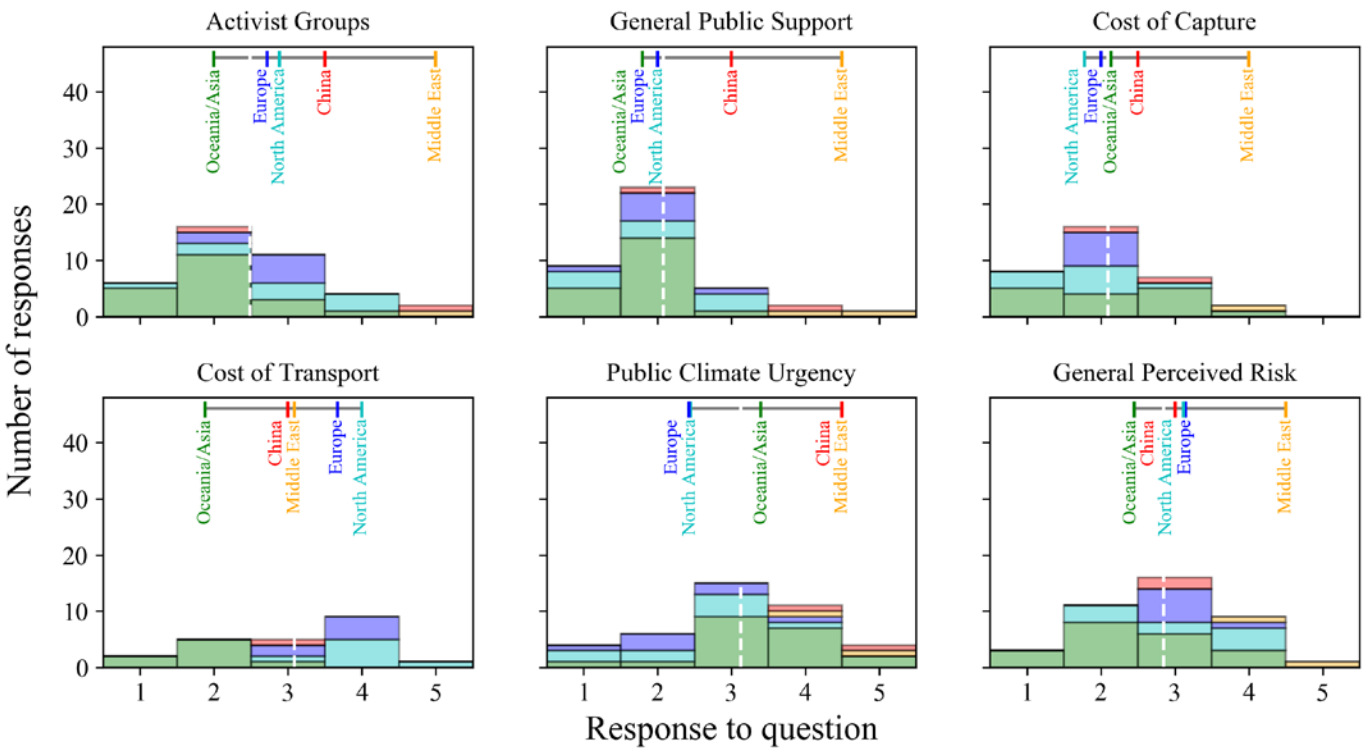


Figure 6: (COLOR) Histograms for the six variables with strong regional dependencies identified in Fig. 5. Each region is colour-coded, with the bar at the top showing the difference in regional means and providing a legend for each region. The white dotted line on the histogram indicates the global mean of all respondents. As with before, a lower response score corresponds to a higher barrier for CCS deployment.

(i) Activist Groups

Activism often plays a significant role in the adoption of technology, and the presence of strong opposition networks in a region can deter investment or cause cancellation. In Australia, the highly publicised "Lock the Gate" movement, which encouraged landholders to prevent property access for the use of coal seam gas exploration, led to mass cancellations of gas license applications [50]. In Europe, organisations such as Wadden Vereniging in the Netherlands attempted to prevent the deployment of wind turbines in their region, citing degeneration of the valued landscape [51]. In the case of CCS, activist groups tend to be more concerned with the potential for “fossil fuel lock-in” [52] and the continuation of society’s fossil fuel reliance [53]. Additionally, activist groups have expressed doubt over the sudden popularity of the technology amongst political groups and the use of the terminology “clean coal”, noting that it is likely driven by financial reasons rather than a legitimate concern for carbon mitigation [54].

Our survey found that the prevalence of anti-fossil fuel activist groups across the various regions was strikingly different, with a 3-point difference (on a 5-point Likert scale) between the lowest regional average and the highest. CCS professionals from the Oceania/S & SE Asia region predominately considered activism to be highly problematic for deployment, which is unsurprising given anti-fossil fuel networks have permeated modern discourse over energy policy, and organised opposition to coal mines and power plants continues to gain strength and public favourability [55]. In contrast, respondents from the Middle East all considered fossil fuel activism to be minimal in their region. This can be attributed to the populist background of many Middle Eastern regimes, meaning collective community action and social movements are relatively uncommon and independent collective mobilisation is frequently outlawed [56]. Those surveyed from China also viewed fossil fuel activism as a low barrier in their region. Much like the Middle East, political conditions still limit the influence of these groups in China, although environmental activism in the region has in recent times become increasingly involved with the transnational environmental movement [57].

Clearly then, this regional variation appears to be primarily driven by political structures and the prevalence of unrestricted social movements and protest. Hence, without sacrificing the principles of free expression and speech, there appears to be little room for learning between the surveyed regions. This is not to say that the influence of anti-fossil fuel activism cannot be better managed through increased transparency in planning and stronger public education regarding the benefits of CCS. Increased public consultation, which was rated as fair across all regions, would do well to increase institutional trust and increase the perceived fairness of local planning processes and technology implementation [34,58]

(ii) General Public Support

Public support has often been presented as a key barrier towards widespread deployment of CCS [12,59]. Concerns regarding storage and pipelines are prominent [12,60], especially when the public feel disempowered in the planning process [58]. Whilst some acknowledge the benefits of CCS in reducing fossil fuel emissions [11], many see CCS as an end-of-pipe solution [23,52], and are concerned that significant investment may cause “fossil fuel lock-in” [52] and detract from competing growth in renewable sectors [13,52]. In fact, there is a strong view that the public would prefer alternative means of carbon mitigation [13].

Similar to the regional variation in activism, respondents were split in their perceptions over general public support for CCS in their regions. Our respondents from the Middle East expressed confidence in public support for the technology (between “High” and “Very High”), an interesting result considering that another study of CCS in Saudi Arabia found that 33.6% of respondents felt that public acceptance was a major challenge in the future of the CCS industry [61]. On the other hand, respondents from the Oceania/S & SE Asia region largely perceived public support as a major barrier, despite prior surveys indicating varied and sometimes positive perceptions of the technology, depending on the level of knowledge [62]. North American respondents were similarly pessimistic, despite prior studies finding that public support in the region is fairly balanced, albeit largely undecided [25]. The divergence in views between the public and the surveyed CCS professionals regarding general public support may be related somewhat to a lack of public awareness, meaning opinions on the technology are not fully formed. As Ashworth et al. [38] suggests, early proactive engagement is the best path forward towards perhaps converging these opinions to a common value.

(iii) General Perceived Risk

Environmental risks such as induced seismicity [13,38,63] have consistently presented themselves as a major concern amongst the public, and on a local level contributing towards an attitude which many associate with “Not-In-My-Backyard”, or NIMBY, beliefs [12,64]. Given the tendency for public acceptability to be predominately based on a risk-benefit basis amongst other cultural factors [16], we would expect environmental risk to demonstrate a converse relationship to general public support. Supporting this, we find similar variability across regions, in that respondents from the Middle East ranked the public’s perception of CCS environmental risk as low, in line with their perception of public support being high in the region, and vice versa for respondents from Oceania/S & SE Asia. Interestingly, this relationship is a much stronger indicator than the perception of environmental benefits, showing that general support for CCS from a public perspective is perhaps much more a function of risk perception.

(iv) Public Climate Urgency

Support for climate change mitigation is often a polarising issue in many countries, and internationally, opinions vary significantly. Past studies find that countries such as those in Latin and South America and Europe are often more concerned about climate change than the US and China, highlighting a negative correlation between level of concern and emissions per capita [65]. This can also be linked to an economy’s dependence on primary natural resources (e.g., agriculture, fisheries and tourism), which are more vulnerable to the effects of climate change and local temperature increases [66]. Similarly, in the case of developing nations, a lack of access to capital may limit the capacity to implement adaptive strategies and technological changes that reduce the effects of climate change.

Amongst our respondents, there was a similar amount of regional variability in the perceived public urgency for climate action. We found that our respondents from the Middle East and China both believed there was a high level of public urgency in their regions, those from Oceania/S & SE Asia rated the perceived urgency as moderate, and European and North American respondents felt public attitudes regarding climate change urgency were low. Whilst views from North America and Oceania/S & SE Asia appear consistent with their emissions per capita, the European responses seem surprising, contradicting the view of Europe as a leader in climate change action [67]. However, since personal livelihoods in most of Europe would likely be less threatened by local temperature increases, perhaps our respondents see climate change support as more of a national obligation rather than a personal ailment [68], and thus less urgent.

Given the link between regions with high urgency for climate mitigation, public support for CCS, and lower perceived risk, this lends itself to an interesting conclusion: more awareness over the personal costs of climate change may lead towards a more positive perception of CCS. However, the problem is largely linked to psychological distance, referring to the notion that people perceive climate change as distant in terms of time, socioeconomic background, geography, and uncertainty. This therefore limits risk for those who are least affected [69]. Whilst increased proximal awareness of the issue may decrease this distance [69], it is a complex approach that can sometimes have no effect unless solutions are seen as feasible or actionable, and in the worst case, can increase scepticism as a defensive psychological mechanism [70]. Additionally, climate change mitigation urgency is a strongly partisan issue in developed nations such as the US [65,68], and hence political preference plays an arguably dominant role in determining perceived risks. In this case, political institutions and structures again hinder the potential for international learning.

(v) Cost of Capture

Capture cost (and recovery) has been cited as the highest economic barrier towards CCS deployment amongst experts [19]. Not only does CCS reduce the energy output of a typical fossil fuel power plant by up to 30% [71], it requires a large incremental capital investment, potentially adding 50-80% to the total investment cost of a conventional pulverised coal plant [19,41]. Additionally, the limited scale of deployment impedes significant investment, due to a lack of information on learning rates [19,23] and high technical and integration risk [10]. Negative learning could also serve to further increase costs, a result of low transparency and high logistical difficulty [8]. For current technology, capture cost estimates vary based on the technology, with 36 – 53 USD/tCO_2 for post-combustion capture at supercritical pulverised coal plants, 48 – 111 USD/tCO_2 for NGCC power plants, and 28 – 41 USD/tCO_2 for pre-combustion capture with IGCC plants [17]

Once again, Middle Eastern respondents were more optimistic, citing costs between $20 and $40 per tonne of CO_2 abated, compared with $60 and $80 indicated by those from North America. This variation can be explained through the diversity of applications, noting that our Middle Eastern respondents indicated a background in oil & gas processing (O&G) (e.g. removal of naturally occurring CO_2 in reservoir gas or capturing CO_2 produced in steam reforming of methane), the capture cost of which is significantly lower than the separation of CO_2 from flue gas of fossil fuel fired power plants [17]. Indeed, the oil and gas sector is already responsible for the majority of currently deployed CCS projects in the form of enhanced oil recovery (EOR) [29]. However, given that EOR essentially facilitates increased oil recovery, focussing on this deployment pathway is likely to be met with public opposition given that it ultimately negates the environmental argument for CCS. Furthermore, circumstances where power plants are located adjacent to EOR operations are rare in practice [20], limiting the widespread potential for lowering capture costs through EOR.

(vi) Cost of Transport

Transportation of CO_2 is also a source of financial uncertainty, in that the costs depend largely upon the geographical conditions and the extent of existing pipeline infrastructure [4]. While transport costs are generally low compared to the cost of capture itself [17], a location far enough from geological storage is likely to create permitting difficulties for large-scale CCS projects [4]. In this regard, we found that our respondents from the Oceania/S & SE Asia region perceived transport costs as around $10 - $20 per tonne of CO_2 transported, a stark contrast to the costs indicated by respondents in North America, at around $2 - $5 per tonne. This discrepancy is due to two factors: likely longer average distances from CO_2 sources to storage sites (thousands of km in some cases) in Australia [72]; and the existing extensive pipeline network already active within the US [73], resulting in little restriction on the flow of shale or non-shale gas between states [74]. Additionally, EOR operations in the US have already facilitated an extensive CO_2 pipeline network. This compares to Australia, where bans on natural gas development have limited infrastructure growth [75] and no EOR operations currently exist. Notwithstanding the geographical differences, there is potential for international learning with regulations, whereby fewer restrictions on natural gas infrastructure may lead to an eventual lowering of transport costs for CO_2.

4.3 Limitations

Several limitations exist within our analysis, primarily a result of sampling size. Firstly, 11% of all responses provided in the survey process were left either blank or as a "Don't Know" response. Respondents were most uncertain about techno-economic factors, with around 48% and 40% of respondents failing to provide an answer for the cost of transport and average long-term injectivity respectively. Testing whether this uncertainty is localised towards one subset of respondents, we find somewhat surprisingly, that the uncertainty in these two variables is spread fairly evenly across all demographics (region, background, knowledge, and experience). This is perhaps a function of scale, in that information such as this is not yet widely known or disseminated due to the small size of the CCS industry. Hence, improving transparency and increasing knowledge transfer amongst professionals in these sorts of techno-economic fields may be important in enabling the growth and consistency of the CCS industry. We do concede however, that this uncertainty in these two variables particularly may be attributed to the project-specific nature of transport and injectivity, which is likely to vary considerably within a given region. Hence, the "average" value for these factors may be difficult to define. Indeed, some respondents expressed concern over this, with one commenting that the "distributions of cost, potential and distance etc. in this region are such that the 'average' views sought may not inform likelihood of deployment". Future surveys regarding perspectives on these metrics should allow a deeper dive into specific locations within regions and include questions that better deal with the variability of these factors.

Another limitation stems from the regional distribution of our respondents, in that the sample we obtained was not fully representative of the global CCS industry. In particular, no responses were obtained from regions such as Africa and South America, and only a few from China (2) and the Middle East (3). Considering that much of the regional variability in the identified barriers stemmed from these latter two regions (where a higher degree of optimism is expressed), we can only speculate as to whether this variability would remain with a larger sample of these regions. The overall sample size (42) of the survey is also small in terms of the types of statistical methods that can be used to test hypotheses, and thus we employed data analysis methods that were more exploratory in nature, intended to identify important variables and relationships to generate hypotheses for future studies.

5 Conclusions

Carbon Capture and Storage (CCS) is a critical technology in decarbonisation scenarios to limit global warming to 2°C and achieving political goals such as the Paris Agreement. However, the lack of successful commercial enterprises within the CCS industry and the failure to meet expectations have raised several question marks over the severity of techno-economic and socio-political barriers within the industry.

Whilst the literature on these topics is extensive, little work has been done to holistically compare barriers that exist globally with those that are highly dependent on the region of interest. Through a survey distributed to CCS professionals worldwide, we aimed to classify variables by their perception and regional dependency, in order to gain an understanding of this comparison.

Initial questioning found that respondents had an overwhelmingly pessimistic view on the ability for the CCS industry to meet decarbonisation scenarios such as the IEA 2DS. This is somewhat contradictory to prior literature, which has generally portrayed those working with CCS as optimistic regarding the future of the technology – a discrepancy we attribute towards provision of the numbers outlining the magnitude of the challenge. We identified a number of universally agreed-upon barriers, which presented themselves in all surveyed regions. These global barriers relate to:

- The extent of existing infrastructure including pipeline networks;
- Regulatory frameworks enabling CCS deployment;
- Public knowledge and awareness of CCS; and
- Landholder compensation to communities neighbouring CCS facilities.

The presence of these barriers suggests significant risk to projections involving rapid scaling of CCS, and highlights key vulnerabilities and uncertainties requiring alleviation. However, these barriers largely exist due to inherent issues within the CCS industry. Additional infrastructure requirements are consistently high due to the necessity for extensive CO_2 pipeline networks. Regulatory frameworks lack clarity due to the highly complex nature of the CCS industry and the fragmented nature of the value chain. Public knowledge is consistently low in all regions due to the lack of CCS projects worldwide, and finally, a lack of landholder compensation is a direct result of unclear regulatory frameworks regarding subsurface property rights in several regions. Whilst clarification and introduction of regulatory frameworks appears to be the logical first step in alleviating these barriers, the complex nature of CCS means that these global barriers will likely remain difficult to overcome in the short-term.

We also identified several variables that demonstrated a strong dependency on the region of expertise of our respondents, indicating that some regions had more favourable conditions for CCS deployment than others did. These variables related to:

- The presence and strength of anti-fossil fuel activist groups;
- General public support for CCS;
- The risks of CCS from the general public viewpoint;
- The public urgency for climate change mitigation measures;

- Cost of capture; and
- Cost of transport;

Whilst the presence of variables with significant regional differences was thought to indicate the potential for international learning, examination suggests otherwise. We found that socio-political factors tend to be limited by political institutions and psychological distance from the effects of climate change, such that regional differences appear to be entrenched into the social beliefs of each separate region. On the other hand, improving techno-economic factors such as capture and transport costs, appears constrained by site suitability and regulatory mechanisms, again making international learning difficult. Despite these difficulties, it is noteworthy that respondents from the Middle East and China demonstrated the most optimism across many variables. This suggests that these regions have the most potential for growth in the CCS industry, although the capacity for this industry to spread worldwide may be limited, harkening back to the difficulties experienced in international imitation of the US shale gas revolution [49]. These regions should be investigated further to increase the sampling size and determine if this optimism persists amongst professionals working in the CCS industry.

Though the survey size for this initial study was small, the analysis has provided some useful insights into the perceptions of professionals towards the barriers and enabling factors for deployment of CCS, and the differences between these perceptions globally. Further research into the regional discrepancies and global commonalities of barriers towards CCS deployment is recommended, as if the CCS industry is to achieve the expansive goals set for it by deep decarbonisation scenarios, it will require careful consideration of how to overcome these difficulties in order to promote widespread deployment.

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PARTICIPANT INFORMATION SHEET

Understanding the technical constraints to the rapid de-carbonization of the power sector.

You are invited to participate in a research project entitled “Understanding the technical constraints to the rapid de-carbonization of the power system in Australia.” This is part of a broader research project that aims to understand the technical constraints to decarbonisation of the energy sector worldwide. This research is being conducted by the Dow Centre for Sustainable Engineering Innovation at The University of Queensland (UQ) in partnership with the UQ Energy Initiative.

Project Outline:
This research project is part of a core project of the UQ Dow Centre for Sustainable Engineering Innovation, in partnership with the UQ Energy Initiative. The broader project aims to understand the current and future technical constraints to the rapid deployment of technologies needed to decarbonize the world’s energy system. In this initial stage we are looking to understand the constraints to deployment of Carbon Capture and Storage (CCS) technologies.

Participant Involvement:
You are invited to respond an online survey. It is expected that the survey will take you approximately 25 minutes to complete. During the survey we will ask you a series of questions to understand your opinions about the technology readiness, deployment and socio-political issues of carbon capture and storage technologies and/or wind power.

Confidentiality and Data Storage:
All information collected will be confidential. The information collected is completely de-identified, and it is not possible to be reconnected to the original responder.

Possible discomforts and risks:
There is no foreseeable risk from this study over and above those faced by you in everyday living. If you have any concerns about the issues discussed in the interviews, please do not hesitate to raise these with the interviewer or The University of Queensland on the numbers below.

Freedom of consent:
Your participation in this research project is entirely voluntary and you may withdraw from participating at any time and without penalty. If you wish to do so, you may simply close your internet browser. If you decide to withdraw, we agree not to use and destroy any data collected from you in the research, unless the withdrawal occurs after the survey has been completed. Your identity cannot be link in any case to the answers you provide.

Feedback on the study:
If you participate in the survey, and you would like to have a say, provide feedback and/or ask any questions that you may think relevant, please email the contacts below.

Queries and Concerns:
This study adheres to the Guidelines of the ethical review process of The University of Queensland and the National Statement on Ethical Conduct in Human Research. Participants can raise queries on the project by emailing Prof. Peta Ashworth at: p.ashworth@uq.edu.au, Dr Simon Smart at s.smart@uq.edu.au or Dr Diego Schmeda at: d.schmeda@uq.edu.au, or calling on +61 7 3346 3883, or using the contacts below.

* 1.

Understanding the technical constraints to the rapid de-carbonization of the power sector - The Case of Carbon Capture and Storage

Please review the information below and tick the box below if you agree to participate in this research project.

By ticking the box below, I acknowledge that:

- I have agreed to participate in the above project being conducted by The University of Queensland.
- I have been provided with information about the project and had any questions regarding my participation and any associated risks and benefits answered to my satisfaction. I understand my participation in the research will involve the following activities: an online survey.
- No data that can be used to identify me has been collected.
- The contact details of the investigating officers are at the bottom of this page and understand that I can contact them at any point during the study. The contact details of an independent ethics officer at The University of Queensland is also listed there, should I wish to raise any concerns or complaints about the conduct of the research.
- I understand that my participation in the project is entirely voluntary and that I am free to withdraw from the study at any time and without having to provide a reason for my withdrawal. However, I understand that if I withdraw the content of my answers will be deleted and not be used in this study.
- I understand that I not may ask for part or all of the information provided by me to be removed from the study due to the impossibility of the investigators to identify my answers.
- I understand that the information I provide for this research will be used for the following purposes: research reports and journal publications and will be treated confidentially. I will not be identified in any publications resulting from the study.
- Information will be stored securely by The University of Queensland and retained for a period of 5 years after which it will be destroyed.
- The survey is design so is of no risk to you, but if you feel like the survey puts you in any form of disadvantage, please contact us using the channels below.
- Sadly, personalised feedback is not possible until the work is finished, this is due to the fact that we cannot identify your particular answer between the pool of answers. However if you have any feedback we would be delighted to hear your thoughts, so please contact us!

In case of any doubts or comments please contact us at:

UQ Dow Centre for Sustainable Engineering Innovation: dowcentre@uq.edu.au or +61 7 334 63883

UQ Ethics (approval #2016001751): humanethicsadmin@research.uq.edu.au

Expert CCS Technology Deployment

General Questions

* 2. In what geographical region are you most familiar with the CCS industry?

- ◯ Asia / SE Asia (incl. India, Australia and New Zealand)
- ◯ China
- ◯ North America (incl. Mexico)
- ◯ Central and South America
- ◯ Europe (incl. Russia)
- ◯ Africa
- ◯ Middle East
- ◯ None
- ◯ Other (please specify)

3. What is your current profession?

4. How many years have you worked with the field of CCS?

- ◯ < 2
- ◯ 2 - 5
- ◯ 5 - 10
- ◯ 10 - 15
- ◯ 15+

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Knowledge Ranking

* 5. In what capacity are you familiar with CCS?

- [ ] Academic
- [ ] Engineering design
- [ ] Geological design
- [ ] Construction
- [ ] Operation
- [ ] Project management
- [ ] Policy making & regulations
- [ ] General knowledge
- [ ] None of the above
- [ ] Other (please specify)

* 6. How would you rate your knowledge in each field of CCS?

	No knowledge	Some knowledge	Informed	High knowledge	Expert knowledge
Capture	◯	◯	◯	◯	◯
Transport	◯	◯	◯	◯	◯
Injection & storage	◯	◯	◯	◯	◯
Policy & regulations	◯	◯	◯	◯	◯
Public support and involvement	◯	◯	◯	◯	◯
Economics	◯	◯	◯	◯	◯
Project management	◯	◯	◯	◯	◯
Environmental effects	◯	◯	◯	◯	◯
Research and development	◯	◯	◯	◯	◯

7. Is there a field of CCS we missed in which you have a lot of knowledge?

8. What sector is the more likely to use CCS in your region?

- ◯ Power
- ◯ Industry / Manufacturing
- ◯ Oil & Gas
- ◯ All of the above
- ◯ Don't know
- ◯ Other (please specify)

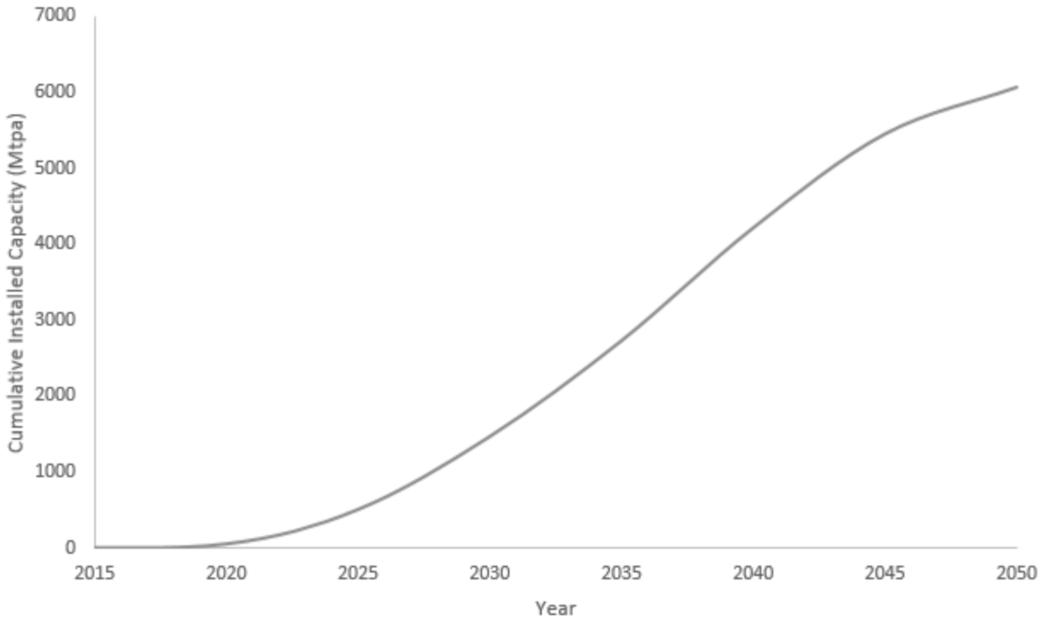
9. How affordable are fossil fuels in your region compared to other energy sources?

- ◯ Significantly more expensive
- ◯ Slightly more expensive
- ◯ About the same price
- ◯ Slightly cheaper
- ◯ Significantly cheaper
- ◯ Don't know

Expert CCS Technology Deployment

Context and Scale

According to the International Energy Agency (IEA), the current CCS installed capacity 27 Mtpa (million tonnes per annum). In order to meet the projections for the IEA 2 degrees scenario, the capacity must increase to 6070 Mtpa by 2050. This requires an average installation rate of 170 Mtpa each year until 2050.



10. In your opinion, what are the chances that the IEA targets listed above are achievable?

- Very low
- Low
- Average
- High
- Very high
- Don't know

11. How many Mtpa of CCS capacity worldwide do you believe are currently installed each year?

- 0 - 1
- 1 - 2
- 2 - 5
- 5 - 10
- 10 - 20
- Don't know
- Other (please specify)

12. What do you believe is the maximum capacity (in Mtpa) that has come online in your region, in the last 3 years?

- 0 - 1
- 1 - 2
- 2 - 5
- 5 - 10
- 10 - 20
- Don't know
- Other (please specify)

13. Assume that there are not constraints from policies, public, red tape, or concerns about costs associated with CCS. What do you believe is the maximum capacity (in Mtpa) that your region is capable to bring online by 2020?

- 0 - 10
- 10 - 20
- 20 - 50
- 50 - 100
- 100 - 150
- 150 - 200
- Don't know
- Other (please specify)

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Technology/Commercial Readiness Level

To answer the following questions, refer to the Technology Readiness Level (TRL) and Commercial Readiness Level (CRL) scale provided.

14. Referring to the above diagram, what is the current TRL (and CRL) of CCS in your region?

- ◯ 1
- ◯ 2
- ◯ 3
- ◯ 4
- ◯ 5
- ◯ 6
- ◯ 7
- ◯ 8 (CRL 1)
- ◯ 9 (CRL 2)
- ◯ 9 (CRL 3)
- ◯ 9 (CRL 4)
- ◯ 9 (CRL 5)
- ◯ 9 (CRL 6)
- ◯ Don't know

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Resource Availability

15. What is the average distance (in km) from major sources that CO_2 must be transported to the perspective sedimentary basins?

	0 - 50	51 - 200	201 - 500	501 - 1000	1001 - 2000	Don't know
First quintile of CO2 generated	○	○	○	○	○	○
Second quintile of CO2 generated	○	○	○	○	○	○
Third quintile of CO2 generated	○	○	○	○	○	○
Fourth quintile of CO2 generated	○	○	○	○	○	○
Fifth quintile of CO2 generated	○	○	○	○	○	○

Other (please specify)

16. How many sedimentary basins, with substantial (10+ Mtpa) of prospective CO_2 storage there are in your region?

17. How would you rate the geological stability of your region? Please think about the likelihood of geological events such as earthquakes

- ○ Very low
- ○ Low
- ○ Average
- ○ High
- ○ Very High
- ○ Don't know

18. Considering the geological stability of your region, how do you think this affects the risks associated with CO_2 storage?

- ○ Very low
- ○ Low
- ○ Average
- ○ High
- ○ Very high
- ○ Don't know

19. What do you think is the total capacity (in Mtpa) of the sedimentary basins in your region?

- ○ 0 - 10
- ○ 11 - 50
- ○ 51 - 100
- ○ 101 - 200
- ○ Over 200
- ○ Other (please specify)

20. What is the average injectivity of the prospective sedimentary basins in your region (Mt/year/well)?

- ○ 0 - 0.1
- ○ 0.1 - 0.5
- ○ 0.5 - 1
- ○ 1 - 5
- ○ Over 5
- ○ Don't know
- ○ Other (please specify)

21. How much of the infrastructure required to reach your regions maximum potential for CCS is already operational? Please include Capture, Transport and Storage

- 0 - 10%
- 10 - 25%
- 25 - 50%
- 50 - 75%
- 75 - 100%
- Don't know

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Economic Considerations

22. On average what are the costs for CO_2 capture per tonne in your region? (US$/tonne)

- ○ 0 - 20
- ○ 20 - 40
- ○ 40 - 60
- ○ 60 - 80
- ○ 80 - 100
- ○ Don't know
- ○ Other (please specify)

[ ]

23. Considering the distances required to transport in your region, on average what are the current costs for transporting CO_2 in your region from capture to the prospective basins? (US$/tonne)

	0 - 2	2 - 5	5 - 10	10 - 20	20 - 50	Don't know
First quintile of prospective CO2 storage	○	○	○	○	○	○
Second quintile of prospective CO2 storage	○	○	○	○	○	○
Third quintile of prospective CO2 storage	○	○	○	○	○	○
Fourth quintile of prospective CO2 storage	○	○	○	○	○	○
Fifth quintile of prospective CO2 storage	○	○	○	○	○	○

Other (please specify)

24. On average what are the likely costs for CO_2 storage per tonne in your region? (US$/tonne)

- ○ 0 - 2
- ○ 2 - 5
- ○ 5 - 10
- ○ 10 - 20
- ○ 20 - 50
- ○ Don't know
- ○ Other (please specify)

25. Given your expertise, how would you rate the following in your region?

	Very low	Low	Average	High	Very high	Don't know
Dollar amount of government incentives to CCS deployment (including carbon taxes)?	○	○	○	○	○	○
Certainty/stability of these government incentives?	○	○	○	○	○	○
Energy demand and growth	○	○	○	○	○	○
Economic environment compared to the current global state?	○	○	○	○	○	○

26. With "Very low" denoting no investments into CCS in your region, and "Very high" denoting CCS as the most profitable energy sector investment in your region, how do you currently view the overall cost competitiveness of CCS in your region?

- ○ Very low
- ○ Low
- ○ Average
- ○ High
- ○ Very high
- ○ Don't know

27. Now consider that CCS is given the same fiscal incentives per tonne abated that other technologies like Wind and Solar receive in your region. How does that change the answer that you gave in Q.26? What is now your assessment of the overall cost competitiveness?

- ○ Very low
- ○ Low
- ○ Average
- ○ High
- ○ Very high
- ○ Don't know

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Public Support

28. Given your expertise, how would you rate the following in your region?

	Very low	Low	Average	High	Very high	Don't know
Cultural / Environmental / Public Significance of the land upon which CCS storage/transport infrastructure is located?	○	○	○	○	○	○
Local environmental risk of CCS or related industries from the public viewpoint?	○	○	○	○	○	○
General environmental concerns about CCS or related industries from the public viewpoint?	○	○	○	○	○	○
Environmental benefits from the public viewpoint?	○	○	○	○	○	○
Prominence of anti-CCS (or anti fossil fuel) networks such as activist groups?	○	○	○	○	○	○
Financial incentives offered to communities neighbouring CCS storage and transport sites?	○	○	○	○	○	○
Consultative processes with communities neighbouring CCS storage and transport sites?	○	○	○	○	○	○
General public knowledge on how CCS works?	○	○	○	○	○	○

	Very low	Low	Average	High	Very high	Don't know
Level of positive previous interactions between communities neighbouring CCS sites and power (or related) industries?	◯	◯	◯	◯	◯	◯
Public support for CCS (or related industries) in communities neighbouring storage sites?	◯	◯	◯	◯	◯	◯
General public support for CCS as a technology?	◯	◯	◯	◯	◯	◯
General public support for other renewable energy technologies? (eg. wind, solar)	◯	◯	◯	◯	◯	◯
Public urgency for climate change action?	◯	◯	◯	◯	◯	◯

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Political Environment

29. Given your expertise, how would you rate the following in your region?

	Very low	Low	Average	High	Very high	Don't know
Level of land use competition for CCS storage and transport sites?	○	○	○	○	○	○
Extent to which the public believe they have influence over the success of local planning approvals?	○	○	○	○	○	○
Average CCS deployment targets set by the governments?	○	○	○	○	○	○
Level of clear policy-driven regulatory frameworks for CCS?	○	○	○	○	○	○

30. With "Very low" denoting a 0-20% chance of final planning approval being granted to a CCS development and "Very high" denoting 80-100% of all funded CCS projects being approved, how would you rate the likelihood of planning approvals for CCS projects being granted in your region?

- ○ Very low
- ○ Low
- ○ Average
- ○ High
- ○ Very high
- ○ Don't know

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Additional Comments

Thank you for participating in this survey!
Please leave any additional comments you find it will enrich this survey.
Your feedback is appreciated.

31. Comments