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LETTER

Public attitudes and emotions toward novel carbon removal methods in alternative sociotechnical scenarios

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Supplementary material for this article is available online

Abstract

Despite high expectations about the role of carbon removal in meeting global climate targets, many of the proposed techniques remain nascent. This is especially so for techniques with potential for large-scale, permanent removal of CO_2, such as direct air carbon capture and storage (DACCS) and ocean alkalinity enhancement (OAE). In such a context, understanding public attitudes is crucial but challenging, since we do not have enough information about the sociotechnical configurations which might accompany such proposals over future timescales. Carbon removal at scale will not take place in a vacuum—it will co-evolve within political, social, economic, and legal structures which in turn will have a strong influence on public attitudes. This study used a nationally-representative survey ($n = 1978$) in the UK to test the impact of alternative sociotechnical systems on public attitudes to DACCS and OAE. Participants were randomly assigned to one of five scenario conditions, representing different forms of governance logic (top–down vs bottom–up) and market logic (planned vs liberal economy), plus one with minimal sociotechnical information. We find that the scenario condition significantly impacted perceptions of OAE, with participants preferring its implementation within a bottom–up, planned economy scenario, and rejecting scenarios which most closely resembled the status quo. There were no significant differences between scenarios for DACCS, suggesting that the technology may be more flexible across alternative sociotechnical arrangements. OAE arouses more negative emotions, particularly worry about impacts on ocean ecosystems, whereas DACCS arouses more hope. We found that climate worry is associated with stronger emotions—both positive and negative—toward both techniques, thus carbon dioxide removal (CDR) could be polarising for the most climate-worried, likely due to tensions between climate urgency and concerns about deterring emissions reductions. The most important criteria for future CDR deployment were deemed to be biodiversity, durability, and cost, with a strong discourse around the current cost-of-living crisis.

1. Introduction

There is a wide gap between the amount of carbon dioxide removal (CDR) required to meet climate targets versus the amount deployed or in progress, of 3.5–5.4 $GtCO_2$/yr by 2030 [1]. This particularly concerns 'novel' techniques which can store the CO_2 for >1000 years, such as those which store the CO_2 deep underground, in minerals or on the ocean floor—such techniques will be vital for avoiding the risk of re-releasing CO_2 [2, 3] but do not yet feature in the climate commitments (NDCs) of any government [1, 4]. Many such techniques are still unproven at scale, or require as-yet-unrealised developments in the broader technical and energy systems on which they depend. Thus we find ourselves in a situation

of reliance on techniques which may not be widely deployed for decades.

Prospects of future CDR deployment in climate policy will also be shaped by public responses to these techniques. It is now well-acknowledged that public attitudes play a critical role in the development and deployment of new techniques [5–7]. However, this creates a significant challenge—how do we understand public attitudes in the context of techniques which do not yet fully exist? At an early stage of technology design and development, it is challenging to know the social and ethical issues which may emerge; yet once a technique is widely-deployed, lock-in means that opinion may already be immovable [8, 9]. Novel CDR techniques lack the developed sociotechnical system required for large-scale deployment [10], but public responses to new technologies will depend in large part on the specific sociotechnical context in which they are developed, incentivised and deployed [11–13]. Carbon removal at scale will not take place in a vacuum—it will co-evolve within political, social, economic and legal structures which in turn will have a strong influence on public attitudes.

With this in mind, we conducted a survey experiment to explore public responses to two major proposals for novel CDR with long-term storage, under different scenarios of the future. Thus the CDR techniques were not viewed as generic artefacts in isolation, but constituted within a broader social, political and economic landscape.

1.1. Framing CDR

A number of survey papers seek to explore the impact of different information frames on public perceptions of CDR [14]. One consistent finding is that framing techniques as more 'natural' tends to improve people's support for the technique [15–18]. Another study found that conspiracy framings significantly lowered support for direct air carbon capture and storage (DACCS) [19], but none of these studies explore sociotechnical systems.

Meanwhile Wenger *et al* [20] tested three different framings of CDR—as a 'technological fix', a 'moral hazard', and a 'climate emergency'—and found that perceptions did not vary between the frames, with respondents generally unfamiliar with CDR. Producing measurable differences between survey conditions experiences a raft of complicating effects, because responses to a frame can be heavily influenced by heuristics, the strength of people's prior attitudes, the information source, and whether the frame is positive or negative [21, 22].

Framing scenarios are also not exclusively the domain of survey studies. Bellamy *et al* [23] tested an experimental deliberative methodology, splitting people into different groups according to their cultural worldviews (see [24]). McLaren *et al* [25] exposed experts to future socio-political scenarios based on cultural theory: Business-As-Usual, egalitarian, authoritarian, and neoliberal. These visions of socio-political futures influenced the framings explored in the current study (see Methods), wherein we also sought to develop and test multifaceted socio-political scenarios, but using a survey framing study with members of the public rather than experts.

1.2. Sociotechnical systems of the future

Technology has long been approached as a site for studying 'society in the making', where competing social arrangements are put on trial in the process of engineering technological systems [26, 27]. The study of sociotechnical systems has shown that the capacities of technologies are not innate but can be interpreted 'flexibly', with technological development understood as a process that involves the progressive redefinition of problems and attendant constructions of social order [28, 29]. Major technological shifts do not just involve the insertion of a new technology into an existing system—they involve a fundamental reconfiguration of the system and all it entails [30]. As scientists, we also hold—consciously or subconsciously—our own ideas of how the future will evolve, as has been demonstrated by work on scientific imaginaries of 'geoengineering' [31–33] and on BECCS [34, 35]. In the case of nascent technologies, researchers must grapple with the challenge of introducing a technology to lay participants without a clear understanding themselves of its precise characteristics, some of which may be the subject to speculation and the object of scientific controversy [36]. Even if we were to agree on what the artefacts themselves might look like—for example, the well-known images of large stacks of fans for DACCS—the socio-political arrangements made durable in the process of development and deployment could vary greatly. Some major CDR proposals are even further upstream: in the case of most ocean-based proposals, most components are still in early-stage testing and will be subject to change in their future configurations, which in turn increases the challenges of anticipating their consequences [37].

2. Methods

2.1. Scenarios

We developed a set of scenarios, depicting divergent visions for future CDR in sociotechnical context, built around two central logics which could influence a future world: the dominant market logic, and the dominant governance logic. These were chosen because of their dual importance in driving sociotechnical change [38], and recognising that governance and markets are mutually reinforcing rather than acting in opposition [39]. Market logic was imagined as a distinction between a liberalised or 'free' market vs a planned economy, with

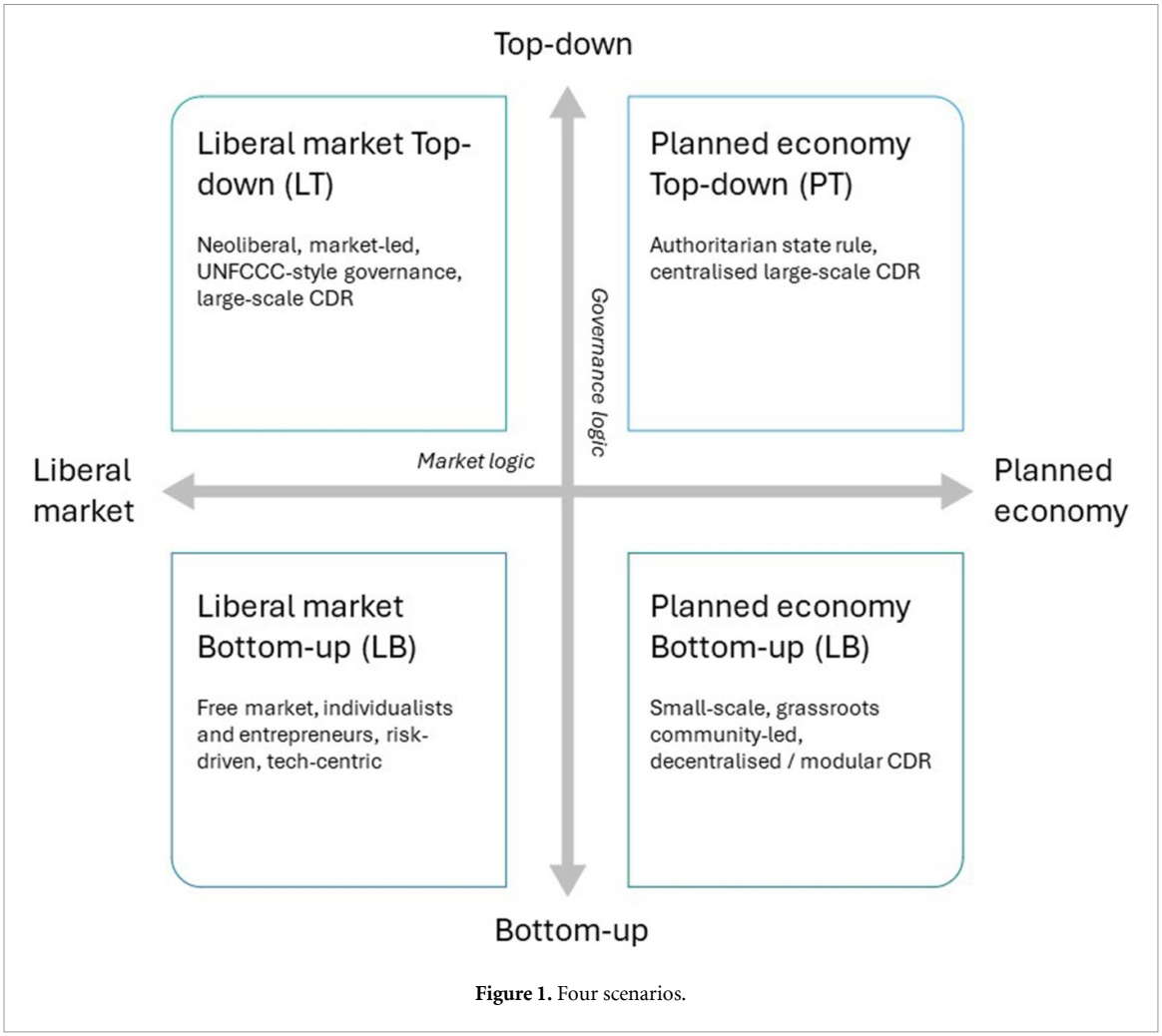

Figure 1. Four scenarios.

the latter including both authoritarian and participatory approaches. Governance logic was imagined as a distinction between top–down, centralised governance vs bottom–up, decentralised governance. Clearly, these are ideal-type situations, and real-world markets and governance will be more complex and nuanced, but these ideal types gave us the basis for building out more complex sociotechnical scenarios. The two axes gave us a 2 × 2 design with four scenarios, shown in figure 1.

We then further elaborated key characteristics of the scenarios, shown in table 1, and used these to develop scenario descriptions to present to survey participants. For each description, we kept the structure the same, but altered key words and phrases to correspond to the scenario, shown in bold in supplementary 3. In addition, we included a 'Basic' scenario which included information on DACCS/OAE, but no specific information on social, economic, or political systems. The scenarios were written for a hypothetical future in 2030 to convey a world where CDR techniques were being developed and upscaled, but not a 'net zero' world (∼2050), and close enough to the present to not be too temporally 'distant' [40]. Participants were not shown the scenario names or the information in table 1, but were simply shown a scenario description and a clip-art-style image: see supplementary 3 for full scenarios and supplementary 4 for design process.

2.2. Techniques

We examined two CDR techniques—DACCS, where chemical reactions are used to selectively react with, trap and extract CO_2 from ambient air, which is then injected into deep geological formations for near-permanent geological storage; and ocean alkalinity enhancement (OAE), where seagoing vessels spread alkaline materials such as silicate or carbonate rocks on the ocean surface, increasing its alkalinity and sequestering CO_2 via near-permanent mineral storage. These techniques were chosen because they represent novel CDR proposals with potential for long-term durable CO_2 storage, but utilising very different capture and storage mechanisms [41]. Both are early-stage techniques which could, in theory, follow multiple configurations as they evolve. For example, some have proposed modular DACCS [42, 43], which represents a very different idea of the future of the technology. For each technique, survey participants received descriptions as part of the scenario framing (Supplementary 3).

Table 1. Key characteristics of the sociotechnical scenarios.

	Basic	Liberal market bottom–up (LB)	Liberal market top–down (LT)	Planned economy top–down (PT)	Planned economy bottom–up (PB)
Governance logic	n/a	Bottom–up	Top–down	Top–down	Bottom–up
Market logic	n/a	Liberal market	Liberal market	Planned economy	Planned economy
Purpose of CDR	n/a	Innovative climate solutions; making money from the carbon market	Meeting global emissions targets	Fulfilling State objectives to tackle climate change	Protecting the environment
Owned and operated by	n/a	New companies, entrepreneurial startups	Multinational companies	State Authority	Local community/CDR co-operatives
Who pays	n/a	Investors	A combination of taxes and private investment	Redistribution of wealth in society	Local community
Source of energy/alkaline substances	n/a	Most economically-attractive sources	Liberal market	State-owned	Locally owned sources

2.3. Survey procedure

Ethical approval for the study was granted by Oxford Central University Research Ethics Committee (CUREC). The survey and scenario descriptions were piloted using face-to-face cognitive interviewing [44] and two online pilots (200 n) (see supplementary 4). The final survey was then distributed to 3910 people by Qualtrics. After data cleaning for duplicates, bot detection, location data, and attention checks, the total sample was $n = 1{,}978$ (see supplementary 1 for sample demographics). The survey consisted of four main sections, shown in figure 2. After answering questions on climate and CDR in general (including a paragraph introducing CDR, see supplementary 2) participants were randomly allocated into one of five scenario conditions ($n = 395/396$), shown a brief description and an image, and asked questions about their opinions on DACCS and OAE, which form the bulk of the analysis in this paper.

We first asked questions about the emotions aroused by the scenario, building on Spence *et al* [45] who found positive/negative affect to be a primary driver of perceptions of a novel CDR technique. Emotions are important for understanding perceptions of techniques in situations of low prior awareness, since people may rely on affect or 'gut feeling' to form opinions, yet there is surprisingly little research on emotions in the field of sociotechnical transitions [46]. We used a set of eight emotions from Midden and Huijts [47], plus an added 'neutral' emotion to enable participants to express lack of strong feeling in a more emotion-oriented way than simply 'do not know'. Participants were asked about their self-reported knowledge and awareness of CDR techniques earlier in the survey, although this is not used in our analysis, since there is little evidence that increased knowledge or familiarity makes people more positive [48–50], and it is more appropriate to focus on people's values and heuristics [51]. Next, participants were asked how 'realistic' they felt the scenario to be (5-point scale plus open-ended question). We deliberately asked the questions relating to the scenario and to participants' emotions first, before moving on to more technology-specific questions, in an attempt to elicit affective feelings toward the scenario as a whole rather than focusing in on the technological components. After this, we asked participants their overall support or opposition toward DACCS (5-point scale plus open-ended). Next, they were asked a matrix question about five pre-defined 'outcomes' of the technique, using items developed by Spence *et al* for eliciting perceptions of novel CDR, plus additional items to specifically explore communitarian and individualist benefits [45]: 'My country's resources (e.g. finances, energy, land etc) should be used to implement DACCS'; 'DACCS would benefit my community'; 'DACCS would benefit me personally'; 'DACCS would be in tune with nature'; 'DACCS would be workable and achievable' (5-point scale). All 5-point scales included a 'neutral/neither support nor oppose/neither agree or disagree' option, but no 'do not know' option; see supplementary 4 for full scales used. Next, participants received a description of OAE corresponding to the same scenario condition, and asked the same questions again for OAE.

All participants were then asked to rank six 'criteria' for future CDR deployment in order of importance, and to propose additional criteria (open-ended). Finally, they were asked twelve questions designed to understand their cultural worldview using the scale designed by Kahan [52], followed by further demographic questions including their location (urban/rural/suburban) political party affiliation, and political views from 'left-wing' to 'right-wing'. The UK political landscape is highly fragmented, with 14 major parties in the survey (including 4 for the devolved nations), therefore the scale approach provides a more direct variable for analysis,

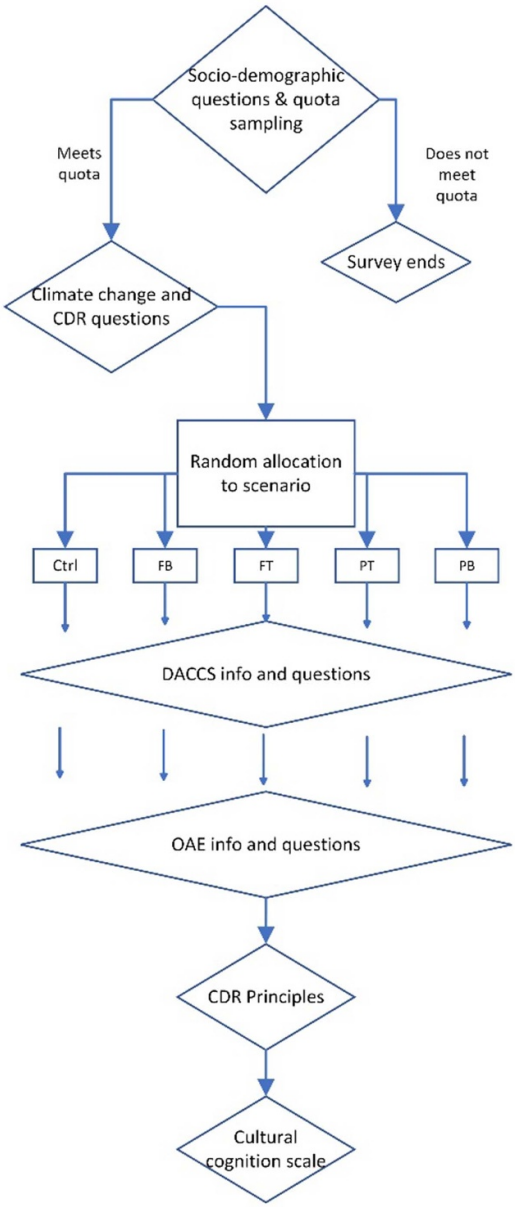

Figure 2. Flow chart showing survey procedure.

although it is limited by the absence of an opt-out option. Full survey questions and scales are in supplementary 4.

The median time taken to complete the entire survey was 13.5 min. Analysis of the data was carried out using IBM SPSS (v25). Details of the tests used are in the following section. Full details of assumption testing are in Supplementary 5. The full anonymised dataset is available via the UK Data Service [53].

3. Results

3.1. Perceptions of DACCS and OAE across scenarios

DACCS was more strongly supported than OAE, across all five scenarios (figure 3). Nearly 50% of participants said that DACCS should play a 'major' or 'somewhat' of a role in addressing climate change (figure 4), whereas participants were less supportive of a role for OAE; a repeated-measures t-test of the mean showed this difference to be statistically significant, $t(1642) = 12.460$, $p = <0.001$ [BCa 0.249–0.342], $d = 0.307$.

DACCS also scored higher for the five 'outcomes' statements than OAE, indicating more positivity, particularly regarding benefits for the community. DACCS was also perceived to be somewhat beneficial for nature (figure 5). Following a PCA to combine the outcome statements (one factor identified, $\alpha = 0.917$ and 0.936), DACCS was shown to encounter less scepticism over outcomes, $t(1977) = 16.683$, $p = <0.001$ [BCa −1.75 to −1.38], $d = -0.375$.

3.2. Comparing scenarios

The sociotechnical scenarios which participants were assigned to had a modest impact on their perceptions of OAE, shown by a one-way ANOVA on the dependent 'support' variable, $F(3, 1973) = 3.626$, $p = 0.006$, $\eta^2 = 0.007$. For OAE, the most preferred scenario was Planned-economy Bottom–up (M = 3.15), followed by Liberal-market Bottom–up ($M = 3.09$), Planned-economy Top–down ($M = 2.94$), Liberal-market Top–down ($M = 2.92$) and finally the Basic scenario ($M = 2.91$), with significant pairwise comparisons (Tukey) between Planned-economy Bottom–up and Basic (M difference = 0.24, $p = 0.027$) and Planned-economy Bottom–up and Liberal-market Top–down (M difference = 0.23, $p = 0.039$) (figure 3). In other words, participants rejected the scenario which most closely reflects current 'business as usual' climate governance (LT), as well as rejecting the scenario which gave no sociotechnical context (Basic), which may also reflect business-as-usual since it does not explicitly differ from the present. However, the effect size was very small, indicating that the scenario was only driving a very small proportion of the variance in the outcomes for the 'support' variable. Meanwhile perceptions of DACCS were not impacted by the scenario, $F(3,1973) = 0.928$, $p = 0.446$. Participants were also asked whether they felt that the scenario they had been given was 'realistic': the responses to this question were strongly correlated with the 'support' question (Pearson's correlation [2-tailed] = $r(1976) = 0.561$, $p = < 0.001$) and showed the same pattern across scenarios, therefore we focus here on the 'support' question.

As a follow-up, we ran two independent-samples t-tests to test for significant differences in participants' 'support' for OAE according to the two axes of differentiation between scenarios—'market logic' and 'governance logic' (see figure 1). For 'governance logic', there was a significant difference in support, with a 'bottom–up' governance logic preferred ($M = 3.12$, SD = 1.13) over a 'top–down' governance logic ($M = 2.93$, SD = 1.16), $t(1581) = -3.261$, $p = 0.001$, $d = 0.052$. The 'market logic' axis on the

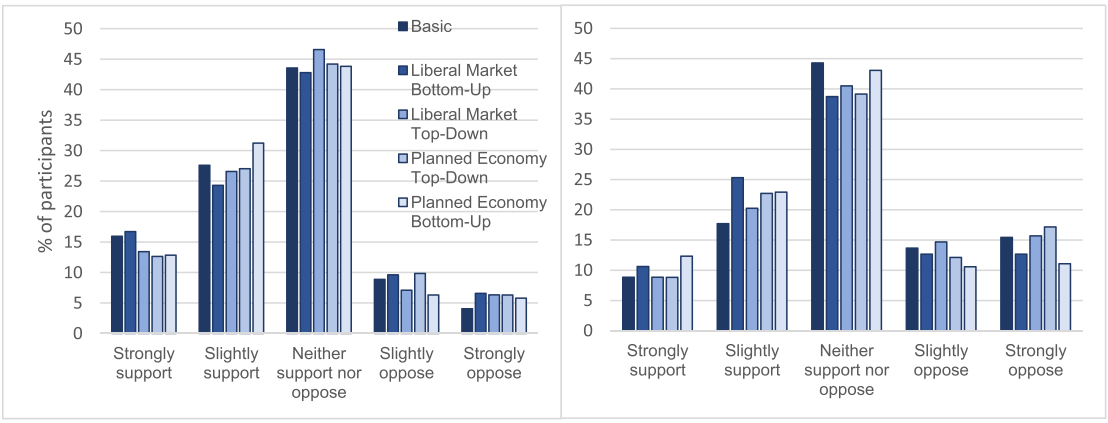

Figure 3. Support/opposition for DACCS (left-hand panel) and OAE (right-hand panel), in different scenario conditions.

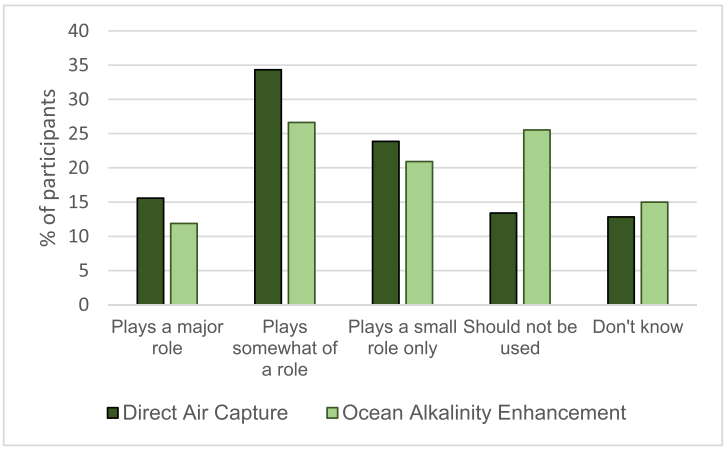

Figure 4. Responses to the question 'Please think about the two techniques you have just read about. How much of a role should each of them play in addressing climate change?'.

other hand made no significant difference to the outcome ($t(1581) = -0.719$, $p = 0.473$). In other words, whether OAE in the future exists within a liberal or a planned economy system does not appear to make a significant difference to people's support, whereas governing it from the 'bottom up' in a decentralised manner appears to be preferred over governing it from the 'top down' with centralised and/or state control.

3.3. Emotional responses

Participants were asked the extent to which they felt particular emotions for DACCS/OAE, on a five-point scale from 'very much' to 'not at all', for a set of eight emotions: worry, annoyance, aversion, fear, powerlessness, satisfaction, hope and calmness, plus 'neutral'. For DACCS, positive emotions such as hope and calmness actually appear to dominate across the five scenarios (figure 6), although worry is also fairly strong. Emotions such as 'fear', 'aversion' and 'annoyance' received lower mean scores (denoting less strength of emotion). For OAE on the other hand, negative emotions came out more strongly, with low amounts of fear but considerably more worry. Similar to the 'support' question, the Planned-economy Bottom–up scenario encounters the most positive emotions.

A PCA (Varimax Rotation) identified two groups of emotions, which we labelled 'positive emotions' comprising satisfaction, hope and calmness (DACCS $\alpha = 0.899$, OAE $\alpha = 0.911$) and 'negative emotions' comprising worry, annoyance, aversion, fear and powerlessness (DACCS $\alpha = 0.885$, OAE $\alpha = 0.905$). As expected, 'neutral' did not load onto either group. A one-way ANOVA showed that for OAE there was a statistically significant difference between scenarios in terms of the emotions reported by participants, both in terms of positive emotions ($F(4,1973) = 2.849$, $p = 0.023$, $\eta^2 = 0.006$) and negative emotions ($F(4, 1973) = 3.304$, $p = 0.010$, $\eta^2 = 0.007$). The Planned-economy Bottom–up scenario encountered more positive emotions compared to the Basic scenario (M difference $= 0.68$, $p = 0.020$), and less negative emotions than the Liberal-market Top–down (M

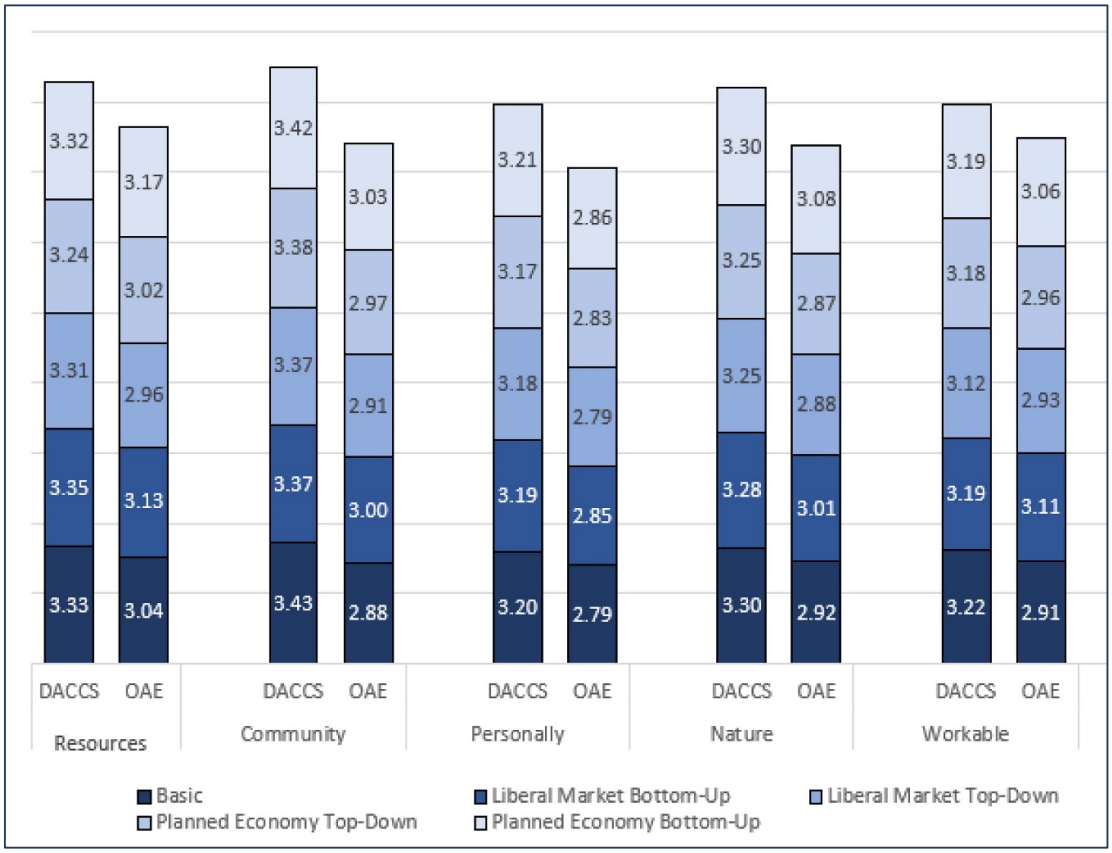

Figure 5. Mean scores for five 'outcome' questions, for DACCS and OAE, by scenario condition. Short-hand shown in bold. 'My country's **resources** (for example finances, energy, land etc.) should be used to implement DACCS/OAE'. 'DACCS/OAE would benefit my **community**'. 'DACCS/OAE would benefit me **personally**'. 'DACCS/OAE would be in tune with **nature**'. DACCS/OAE would be **workable** and achievable'. 5 = 'Strongly Agree'. 1 = 'Strongly disagree'.

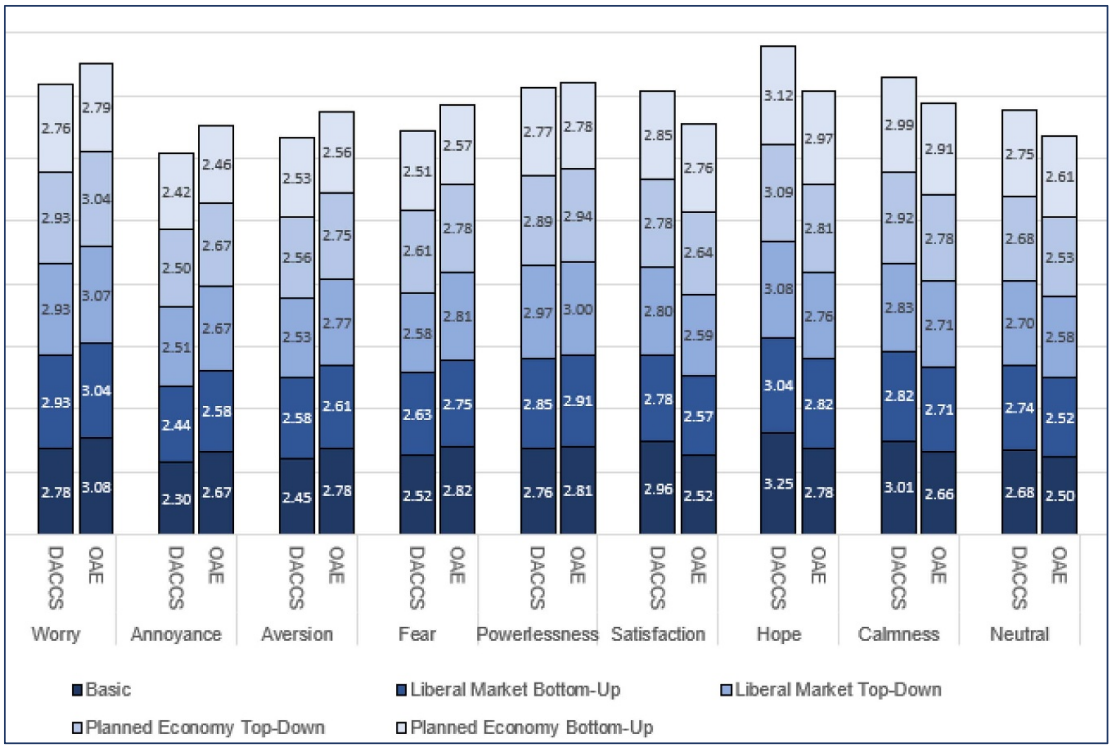

Figure 6. Responses to the question 'When considering this scenario, to what extent do you feel the following emotions? Mean scores by scenario condition. Mean is from a 1–5 scale, 5 = "very much". 1= "not at all"'.

diff = 1.16, $p = 0.012$), Liberal-market Bottom–up (M diff = 1.03, $p = 0.037$), and Basic scenarios (M diff = 0.10, $p = 0.046$).

3.4. Determinants of emotions

Additionally, we ran a multiple regression analysis to identify the main drivers of positive and negative emotions, shown in table 2 (assumption testing in supplementary 5). 'Emotions' were used as a dependent variable due to their importance for understanding perceptions of less-known technologies, and their relatively underexplored status in the literature on sociotechnical transitions (see Methods); they also enabled us to differentiate between positive and negative emotions. The results support the ANOVA above, as well as the results of the tests using 'support' as the dependent variable: the sociotechnical scenarios generally do not act as significant predictors, with the exception of the Planned-economy Bottom–up scenario for OAE. Surprisingly, cultural worldviews are not a particularly consistent driver of emotions across the scenarios, although those with Communitarian worldviews feel significantly less positive toward both DACCS and OAE than the reference scenario of 'Hierarchical Individualist'. As expected, those in favour of CDR generally feel more positive and less negative about both DACCS and OAE. Interestingly, it appears that greater worry about climate change is associated with stronger emotions, both positive and negative. The open-ended data shown in the next section give a possible reason for this: some see the urgency of climate change as justifying a need for novel CDR, whereas others worry about deterring tried-and-tested emission-reduction techniques.

Finally, we find that those who self-identified as further toward the 'right-wing' end of the political scale feel both more positive and more negative toward DACCS and OAE. This is potentially an artefact of how the data has been aggregated into compound scales, or of the lack of opt-out option in this question in the survey; however, one possible explanation is that some of these participants think that novel CDR can work with the grain of the market (more positive emotions), whereas there are also those who believe we should be prioritising other things above climate change (more negative emotions). This could be interesting to explore further in future work.

3.5. Open-ended responses

For DACCS, the open-ended responses showed many of the same concerns identified in previous research, around storage, safety, and leakage. Participants also expressed concerns about the long-term sustainability of the idea, although some perceived environmental benefits; the latter group often echoed a 'climate urgency' framing, for example, '*I only see a complete need to combat the climate emergency and I really like this idea*'. A strong narrative was around cost and affordability, particularly for the scenarios involving for-profit enterprises (Liberal-market Bottom–up) and taxation (Liberal-market Top–down, Planned-economy Top–down). Participants felt that the expenditure would be unfeasible or inequitable in current times: '*How can we afford to do that during a cost-of-living crisis?*'. Overall however, the strongest theme was around uncertainty, indifference, and/or a sense of not knowing enough. In most cases not enough information was given to distinguish between these categories of response—for example, to say whether the uncertainty stemmed from lack of knowledge or indifference (see quotes in next paragraph). In addition, 4.7% of participants ($n = 94$) did not engage with any of the three open-ended questions in any meaningful sense, with responses like 'n/a', 'idk' 'nothing'. Together, this may provide a possible explanation for the lack of significant differences between the sociotechnical scenarios for DACCS. Despite the fact that the Basic scenario gave no information about the sociotechnical context, the level of uncertainty/indifference here was similar to the other scenarios, suggesting that the additional sociotechnical information was not assisting participants in imagining the technique.

The open-ended responses for OAE might give valuable information about *why* there was a significant difference between survey scenarios here. However, across all scenarios, two very strong framings appeared to be driving the majority of responses. Firstly, a sense of uncertainty and/or indifference, similar to the DACCS scenarios, might explain why the effect sizes for the inter-scenario comparisons were so small; for example, '*I am indifferent because I do not know enough about it*' and '*[I feel] a sense of apathy and indifference*'. Secondly, concerns about ocean impacts were found strongly across all scenarios—in particular, concerns about 'polluting the ocean', with the term 'pollute' appearing 78 times in the responses, along with a great many responses about ocean waste, ecosystem impacts, and 'tampering with nature' perceptions. This may explain why the emotions which OAE aroused were more negative than for DACCS. Perceived ocean impacts far outweighed concerns about cost. OAE is seen by many as potentially divisive across all scenarios, e.g.: '*I suspect this plan may become a very divisive one, with*

Table 2. Multiple regression results for dependent variables 'positive emotions' and 'negative emotions' (factored together), for DACCS and OAE.

	DACCS				OAE			
	Positive emotions [e]		Negative emotions [f]		Positive emotions		Negative emotions	
Variable	B	β	B	β	B	β	B	β
Constant	3.40		13.25		3.70		12.46	
Age	−0.16**	0.09	−0.21*	−0.07	−0.32**	−0.17	0.07	0.02
Gender [a]	0.30	0.05	−0.15	−0.02	0.36*	0.06	−0.13	−0.01
Climate change worry	0.17**	0.14	0.45**	0.23	0.22**	0.17	0.42**	0.19
CDR attitude	1.06**	0.35	−1.04**	−0.21	0.81**	0.25	−0.78**	−0.15
Worldview [b]: EI	−0.06	0.01	0.32	0.37	0.13	0.01	0.17	0.01
Worldview: HC	−0.48**	0.08	0.12	0.01	−0.33*	−0.05	0.14	0.01
Worldview: EC	−0.89**	0.12	0.76*	0.06	−0.45*	−0.06	0.74*	0.06
Location [c]: Rural	−0.23	0.03	0.29	0.03	−0.31	−0.04	−0.14	−0.01
Location: Suburban	−0.20	0.03	−0.32	−0.03	−0.26	−0.04	0.27	0.02
Politics left/right [d]	0.16**	0.11	0.23**	0.10	0.13**	0.09	0.28**	0.11
Scenario: LB	0.44	0.06	0.61	0.05	0.29	0.04	−0.31	−0.02
Scenario: LT	0.36	0.05	0.69	0.06	0.24	0.03	0.14	0.01
Scenario: PT	0.30	0.04	0.66	0.06	0.42	0.05	−0.04	0.00
Scenario: PB	0.01	0.01	0.14	0.01	0.89	0.11	−1.00*	−0.08
R^2	0.24		0.70		0.18		0.05	
F	44.22**		10.43**		31.06**		7.68**	

$n = 1978$ * $p < 0.05$ ** $p < 0.001$. B: Unstandardized Beta Coefficient. β:Standardized Beta Coefficient.

[a] Gender: Recoded into dichotomous variable 'male' and 'female' (together representing 99.51% of participants) Female = 0, Male = 1.

[b] Worldviews (cultural cognition scale): Recoded into dummy variables. EI = Egalitarian Individualist, HC = Hierarchical Communitarian, EC = Egalitarian Communitarian. (reference category Hierarchical Individualist).

[c] Location: Recoded into dummy variables (reference category Urban).

[d] Participants asked to position themselves on a 1–10 scale from 'left-wing' (1) to 'right-wing' (10).

[e] 'Positive' emotions: satisfaction, hope, calmness.

[f] 'Negative' emotions: worry, annoyance, aversion, fear, powerlessness.

lots of spin being hurled from one side of Parliament to the other!'. Interestingly though, the social and political barriers tended to be explicitly connected to environmental risks, e.g. *'A lot of social unrest due to effectively what will be seen as polluting the oceans and altering their ecosystem; a political hot potato'*. This contrasted the DACCS open-ended responses, which mainly focused on socio-economic issues.

We tried to unpick why the small-scale decentralised scenario (PB) was preferred for OAE, and identified a strong theme of 'social benefits' connected to ideas of local economy and bringing communities together: *'Socially it would be of benefit to communities as they would be involved and have some control. Having people working together for the greater good would bring hope'*. Therefore the differences in the OAE scenario appear to reflect perceived *benefits* for people and communities—particularly salient in light of the strong discourse around cost-of-living pressures. It is also interesting that this difference did *not* occur for community-based, modular DACCS. The PB scenario still encountered concerns about tampering with nature in the ocean, but the concern was balanced with many positive responses about the impacts on the environment, e.g. '*Would be good as it will help the environment. If people were able do this locally to them then it would be a positive outcome for everyone*'.

3.6. Criteria for future deployment of CDR

At the end of the survey, participants were asked to rank six pre-defined criteria for CDR deployment: low risk of carbon re-release (durability); biodiversity benefits; job creation; low land-use requirements; long storage period (permanence); and accurate measuring and monitoring (MRV). We found a clear preference for biodiversity across all scenarios, and also a preference for durability (figure 7), with the other criteria ranked much lower and MRV in last place. However, the 'durability' result may reflect the way the question was worded, which gave the example of re-release 'by forest fires', therefore it may be that some participants misread the question and thought DACCS/OAE might *cause* forest fires. The ranking difference was significant as $F(4.83, 9555.53) = 393.39$, $p = <.0005$, $\eta^2 = 0.166$ (one-way repeated-measures ANOVA), and all pairwise comparisons were statistically significant except for jobs vs land use, and land use vs permanence. A

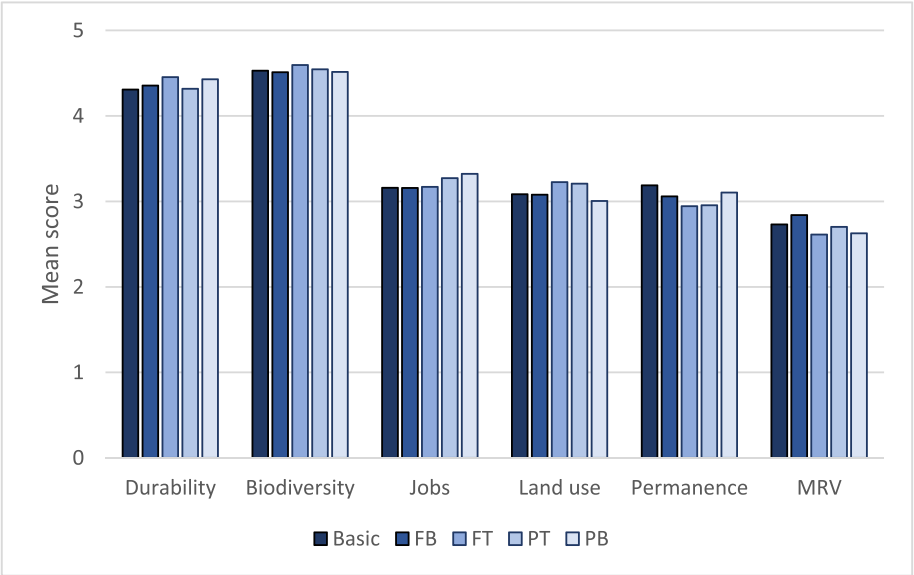

Figure 7. Responses to the question, 'When thinking about techniques for carbon removal, please look at the following six principles and rank them in order of importance. Reverse-coded: 6 = most important, 1 = least important. Mean ranking across all participants, by scenario condition'.

word frequency analysis on the open-ended question inviting additional proposed criteria (supplementary 6) showed priorities for 'carbon' (reflecting a belief that CDR needs to be effective) and 'cost' (reflecting affordability concerns and cost-of-living crisis), plus 'nature', 'environment' and 'wildlife'.

4. Discussion and conclusions

The coming decades may bring significant social, political and economic shifts, making it challenging to predict the sociotechnical arrangements which will accompany and influence CDR upscaling. Therefore, it is important to consider possible future social and political arrangements when examining possible public responses [11, 25, 54, 55]. We carried out a survey study of perceptions of DACCS and OAE, under different sociotechnical future scenarios. This is a novel methodological approach for exploring lay public perceptions, examining CDR in the context of holistic scenarios which include interlinked and internally-consistent social, political and economic aspects. Thus, we aim to examine not just *what* people think about CDR, but also the impact of how CDR is to be governed and incentivised, providing crucial insights on what the enabling conditions for the most socially-robust CDR might look like. In addition, we explore people's attitudes and emotions, both of which will be crucial for CDR upscaling: decisions about climate interventions will not be a purely cognitive process, and people's emotions will play a crucial role [46, 56, 57], particularly for highly novel innovations such as long-duration-storage CDR which could prove disruptive and/or transformational.

We find that perceptions of OAE were impacted by the scenario framing, whereas perceptions of DACCS were not. For OAE, participants marginally preferred the scenario with bottom–up, decentralised governance arrangements and their perceived benefits for the community and local economy. Participants largely rejected the scenarios which most reflected current climate governance. Therefore achieving socially-robust OAE might require consideration of alternative arrangements for incentivisation, financing, and governance, with participants preferring a localised model where the community shares responsibility and liability. For example, projects could explore alternative community-led ownership arrangements [58]. Future research could interrogate which future governance arrangements (if any) are being assumed by current marine CDR deployment projects, and the extent to which alternatives are being considered or enacted. We also found a very strong tendency for participants to focus on environmental issues relating to the ocean, in-line with previous research showing that ocean-based techniques might encounter heightened risk perceptions due to emotional responses and perceptions of 'taboo' trade-offs [59, 60]. Ocean techniques may be perceived as taking place in open, interconnected systems wherein unintended consequences may be more difficult to monitor, control, and ultimately reverse [23, 59], whereas onshore DACCS by contrast might be seen as a more 'contained' system. It is worth noting that we only tested open-ocean OAE, including in the decentralised scenario ('small boats'): coastal OAE, which is also a topic of current research interest, was not explored in this survey and might not experience the same concerns about open ecosystems [61].

Participants' preferred criteria for future CDR deployment also reflected this strong concern for biodiversity, wildlife and 'nature', supporting previous work on the importance of 'messing with nature' perceptions [16, 62, 63], and suggesting that reducing adverse ecosystem impacts may be a crucial criteria for CDR deployment in the UK. Participants also expressed a preference for 'durable' CDR solutions, which is interesting as these two goals might be quite challenging to achieve simultaneously, since the CDR techniques which could enhance biodiversity are also often those with shorter-term storage [64, 65] (although we note caution over the wording of the 'durability' criteria, see above).

Meanwhile, DACCS was generally preferred to OAE. Interestingly, portraying DACCS as small-scale and community-led did not lead to different perceptions in the same way as OAE, with modular DACCS encountering similar degrees of hope, worry, ambivalence, and concern about physical risks, and no significant differences between scenarios. This suggests that DACCS may be a more socially 'flexible' technology, in that it is deemed—by UK publics at least—to be suitable across a wider range of possible implementation contexts than OAE. Further research would be needed to understand whether this can be generalised to other deployment contexts, for instance in places with a legacy of analogous technologies. However, the potential for DACCS to create increased pressure on public finances, and for costs borne by government or companies to be passed on to consumers, was a clear risk in the minds of our respondents. This could be critical in how a programme for DACCS upscaling would unfold in the UK, and potentially in other countries experiencing cost-of-living pressures since the pandemic. Reducing uncertainty over the costs of novel CDR would greatly assist in both studying public perceptions and in communicating CDR messages to the general public.

DACCS aroused more positive emotions than OAE, particularly 'hope' and 'calmness', whereas OAE aroused more negative emotions, particularly 'worry'. The most important predictors of participants' emotions were support for CDR in general, political views, and climate worry. Interestingly though, heightened climate worry was associated with both more positive *and* more negative emotions. From the open-ended data, it appears that whilst some perceive climate urgency as a justification for any novel CDR [37, 66, 67], others are worried about CDR being used as a 'band aid' or deterring emissions reduction efforts [68, 69]. This implies that communicators should be more cautious about the use of the 'urgency' framing, since it may elicit very different emotional responses from people. However, further research is needed to understand this apparent polarisation of CDR views amongst the most climate concerned, and whether it may be generalisable to other socio-political or geographical contexts.

Importantly, our scenarios drew attention to the overriding *purpose* of the CDR techniques, which is seldom made explicit in scenarios or policies, but which diverged considerably in our four visions of the future (table 1). As Stilgoe [70] points out, purposes matter: people care about the eventual purpose of a technique and the sort of world it envisages (see also [71, 72]). The purpose of CDR is a matter of debate: CDR is often proposed as a compensation for 'hard-to-abate' or 'residual' emissions, yet these have not been properly quantified and rely on socio-political assumptions which have been relatively devoid of scrutiny [73, 74]. Of course, in practice CDR might be implemented for a variety of overlapping purposes; however, attempting to achieve multiple co-benefits is difficult in practice [75], and there is often an underlying rationale which expresses itself via the governance and market arrangements, even if it is not explicitly acknowledged [76]. In the preferred OAE scenario (bottom–up planned-economy), the underlying purpose of CDR was to 'protect the environment', which is consistent with participants' prioritisation of environment and marine ecosystem protection, the strongest theme across all five scenario conditions in the OAE open-ended responses. Thus the significant preference for this particular scenario could potentially be explained by the internal consistency between people's priorities and the underlying purpose of CDR in the scenario.

A limitation of this study concerns the way in which participants were asked about both DACCS and OAE. This did enable us to run within-subjects tests on the two techniques, but will have introduced an ordering effect, in that DACCS may have acted as an 'anchor' upon which subsequent responses to OAE were made [77] (although we note that the OAE responses did broadly support the existing literature). A follow-up study could utilise a factorial design where participants are assigned to one technique only. Responses also revealed large amounts of indifference and uncertainty, which is to be expected for work on novel techniques with low prior knowledge, but also reminds us that perceptions will be conditional and malleable [66, 67]. Importantly, this was the case for all scenarios, therefore the additional sociotechnical information did not appear to assist participants in imagining the techniques. Similarly weak or unstable responses to information frames have also been found in other studies on novel climate interventions [20, 78, 79]. It may be that confronted with so much new information, not only about an unfamiliar technology but also an unfamiliar sociotechnical world, some of our participants experienced information overload.

With scenario work, it can also be difficult to identify which aspects participants were focusing on, and which aspects they were ignoring or subconsciously challenging [80]. In an attempt to be holistic, our scenarios combined multiple different

characteristics, making it difficult to know which specific aspects participants were responding to, which has implications for the replicability and generalisability of our findings. The open-ended analysis does help us to unpick participants' responses to particular scenario features, and future work could use qualitative approaches to delve more deeply into nuances within and between scenarios. Moreover, if something conflicts with priorities which people value—for instance, being fair, clean, or renewable—people may perceive it negatively regardless of the survey framing [81]. For example, the perception of environmental impacts or unfair allocation of costs could represent a fundamental value conflict for many people, potentially acting to override the sociotechnical scenario information we had provided.

Data availability statement

All source data for this study is publicly available via the UK Data Service. DOI: https://doi.org/10.5255/UKDA-SN-857271.

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Conflict of interest

The authors declare that the work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Ethics statement

This research was carried out in accordance with the BPS Code of Human Research Ethics. Ethical approval for the study was granted by the University of Oxford Central Research Ethics Committee (CUREC), approval code SOGE C1A 23 78.

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