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UK public reaction to carbon dioxide transport and temporary storage at ports

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Abstract

Achieving net zero carbon dioxide emissions will require investment in large-scale logistical infrastructure to remove, transport, and store carbon dioxide from the atmosphere, exhaust gases, and waste streams from industrial plants. Successful implementation of carbon capture, storage (CCS) will depend on stakeholder investment and public agreement. Evidence of how the public perceive methods of CCS and their preferences among potentially viable options remains scarce. To gain knowledge of likely public reaction we elicited perceptions of CCS and transport, as well as preferences for different CCS capture, storage, transport, and regulation options, via a UK representative on-line survey ($n=1070$). Compared to three other industrial substances (hydrogen, ammonia and LNG) perceptions of transport and storage of carbon dioxide were somewhat favourable, indicating public reaction towards carbon dioxide shipping and temporary storage at ports is moderate, reducing the likelihood of major controversy. When considering preferences for alternative CCS and transport options, the most important factors of those evaluated were Regulation and Transport. The most preferred approach involved international or government regulation and pipeline transport, with industry self-regulation receiving the least support. These findings suggest the use of pipelines or where necessary ships and either international or government regulation are promising pathways to increase the chances of public acceptance of CCS.

Keywords Carbon capture storage and transport · Carbon dioxide transport via pipelines and ships · Port storage of industrial substances · Public perceptions of CCS options

1 Introduction

The IPCC Sixth Assessment Report highlighted the need to capture and store carbon dioxide at global scale to reach net zero greenhouse gas emissions targets (Allan et al., 2021). Meeting this need will involve chemical processes to capture carbon dioxide from the atmosphere, exhaust gases, or waste streams from industrial plants, and then transport captured and purified CO_2 to sites for long term (100s to 1000s of years) safe storage in geological

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reservoirs. For western Europe much of this geo-storage will be offshore in either exhausted or partially depleted oil and gas reservoirs or deep saline aquifers (Bentham et al., 2014: CO_2GeoNet, 2021). However, because many large industrial sources do not have locally available geo-storage reservoirs, captured CO_2 will need to be transported substantial distances from source to reservoir (100s of km). Although carbon capture and storage (CCS) at industrial and power generation sources is vital to limiting global warming below 2 °C, implementation of CCS projects remains slow (Bui et al., 2018).

In the UK, carbon capture and storage are acknowledged as essential technologies to reach binding commitments for Net Zero by 2050. Government policies include ambitions to capture 10Mt of CO_2 by 2030 but investment and deployment lag behind posture (e.g., 6th Climate Change Committee budget; HMG 10-point plan, 2020; Powering up Britain, 2023; CCC-response, Spending Review, 2025). Also, the deployment of CCS technologies at scale requires early public consultation and general support for CCS.

Internationally, CCS projects have met mixed public response and, in some cases, cancellation or years of delays due to public opposition (Brunsting et al., 2011; Dütschke, 2011). Insufficient regulations and common infrastructure are also cited as barriers to implementation (Lockwood & Bertels, 2022). However, recent law changes and investment into CCS development have prompted developments such as the London Protocol that allows cross-border CO_2 transportation and storage and provides the possibility of common interest CCS projects across Europe (Merk et al., 2022). The second stage of Norway's Northern Lights project, planned for 2025, is an example of a venture that intends to capture and ship industrial CO_2 from sites across Europe that will be stored temporarily onshore, then pipelined offshore to a long-term storage injection site in the North Sea (Merk et al., 2022). As of 2022, the Clean Air Task Force note that over 50 carbon capture or storage projects with the potential to abate 80 Mt of CO_2 per year are proposed across Europe, demonstrating the impetuous for project deployment and urgent need for public engagement.

In developed countries public awareness of CCS projects and the various options for capture, storage and transportation is low (Mabon et al., 2015; Zhang & Huisingh, 2017; Bellamy & Raimi, 2023), confirming the need to inform the public and consider their perspectives in the early stages of potential CCS projects, ensuring progress is democratic, cooperative, and amicable. To avoid public mistrust and opposition it is important to build trust through inclusion (Bellamy, 2022). Involving citizens in key decision-making can help identify acceptable pathways to CCS implementation while providing concerned citizens with the opportunity to influence decisions that will ultimately affect them. Additionally, knowledge of public concerns allows stakeholders to make decisions that are more aligned with the public's views and thereby lessen the potential for conflict (Selma et al., 2014).

Meeting the UK's commitment to upscale CCS deployment will also require a substantial transport network. Although some studies have investigated perceptions of, or preferences between, options for capturing and storing CO_2, (e.g., Mabon et al., 2015; Whitmarsh et al., 2019), few have specifically investigated public perceptions of or preferences for the transport of captured carbon dioxide (Tcvetkov et al., 2019). This gap is surprising given transportation of CO_2 is a critical part of the CCS process for many industrial sources. The requirement for structures such as pipelines or storage tanks at ports that will be highly visible to the public mean that there is potential for strong public reactions.

The present research therefore fills an important knowledge gap by providing early indications of likely UK public reaction to CCS transport and temporary storage at ports. It does so using two methods from consumer research that are designed to minimise response bias and ensure the robustness of the resulting estimates.

First, we draw on associative network theories of memory and related metrics from consumer and public engagement research (Anderson & Bower, 1974; Romaniuk, 2013; Wright et al., 2014; Carlisle et al., 2020). These measures capture cognitive associations related to the transportation and storage of carbon dioxide. To control for baseline response tendencies within the sample we appraise these perceptions against three comparable industrial cryogenic substances: hydrogen, ammonia, and LNG.

Second, we evaluate implicit preferences for various CCS implementation profiles through Best-worst scaling methodologies developed in marketing and economics (Louviere et al., 2015; Flynn & Marley, 2014). These procedures used trade-off analysis to reveal the most important general factors and relative preferences for alternative implementations of these factors in CCS and temporary storage. Our dual approach aims to provide actionable insights for policymakers and industry stakeholders, while avoiding the subjectivity and framing effects of standard survey question approaches.

As one of the few studies to quantify public preferences for CCS inclusive of transport options, the results provide rare empirical evidence to support regulators making policy decisions about CCS and transport investment, while also adding to the growing literature on public engagement with CCS. The findings and implications for public engagement will support researchers, industry, and policymakers in considering deployment of these essential technologies.

The remainder of this manuscript is structured as follows. Section 2 reviews prior literature on CCS perceptions, storage, and transport. Section 3 outlines the study methods. Section 4 presents the main results, while Sect. 5 discusses their implications for public awareness, perceptions, and trust. Section 6 distils the findings into specific policy implications. Finally, Sect. 7 concludes by summarising contributions and outlining directions for future research.

2 Literature review

Global CO_2 emissions rebounded to a new record of over 36.3 Gt in 2021 (IEA, 2022), following the covid-19 economic slowdown in 2020. To avoid damaging levels of global warming and climate change impacts, CO_2 will likely need to be captured and stored. Capture could be carried out either by the production of electricity from the combustion of bioenergy crops combined with CCS – (BECCS) (Fuss et al., 2018) or through engineered structures to filter CO_2 from the atmosphere, known as Direct Air Capture and Carbon Storage (DACCS). The relatively low concentration of CO_2 in the atmosphere (~420 ppm in 2022) makes large scale capture challenging. Conversely many stationary industrial sites, ranging from electrical power generation, iron and steel, cement, fertiliser, paper and pulp, to oil refining and petrochemicals production, emit exhaust waste streams with high concentrations of CO_2 that may be more easily captured before they are emitted (Leeson et al., 2019).

Once captured, CO_2 requires secure storage so that it does not leak back into the atmosphere. Storage options considered viable for long term CO_2 sequestration due to their large global storage capacity include depleted oil or gas reservoirs and saline aquifers (Benson et al., 2012; National Research Council, 2015). The public have diverse concerns regarding the integrity of storage options, and the relative preference for onshore and offshore storage may vary by country (Ashworth et al., 2015).

Other CO_2 storage options include unmined coal beds and the deep oceans. Unmined coal beds (that also allow methane gas recovery) were considered suitable for CO_2 storage in tests carried out in Canada and the US; while large areas of old unmined coal bed are available, many sites across Western Europe and China are not economical due to low permeability or porosity (Leung et al., 2014). Storage in the deep ocean has also been suggested but raises environmental concerns such as ocean acidification (Leung et al., 2014) and extinction of benthic fauna (Carroll et al., 2014).

Although perception of the suitability of storage sites varies between countries and regions, some countries are also restricted by the availability of locations. For the UK, there is only limited onshore CO_2 storage capacity, whereas there are abundant offshore locations primarily in the North Sea but also the East Irish Sea and English Channel (Gammer et al., 2011).

As CO_2 point sources and consequently capture locations often do not coincide with sites for permanent geo-storage, transportation of captured CO_2 is an essential component of the CCS system. Currently, over 6,500 km of pipelines in North America, Australia, Europe, and Africa carry dense or gaseous CO_2 from large power and industrial plants to onshore and offshore storage sites (Vianello et al., 2016) while large networks of additional pipelines are used for other industrial purposes and particularly enhanced oil recovery. At a large scale, pressurised pipelines are expected to account for the majority of CO_2 transportation, although ship transport is also considered practical over large distances (Bui et al., 2018). The cost of shipping is mostly operational (Vakili et al., 2025), whereas developing a network of pipelines requires substantial new infrastructure investment. Other possible transportation methods are rail or road tankers, although these are only a cheaper option in the short-term and at lower scale over short distances (Leung et al., 2014).

Public perceptions of carbon capture and storage (CCS) have long been a critical area of inquiry. As with many emerging technologies, public opinion is constrained by lack of awareness and susceptible to framing effects (Mabon et al., 2015; Whitmarsh et al., 2019). Early investigations (e.g., Tokushige et al., 2007; L'Orange Seigo et al., 2014) revealed that limited public awareness and heightened risk perceptions were common, with unfamiliarity often magnifying concerns even when technical assessments indicated low hazard levels, although benefit perceptions and provision of natural analogues could increase acceptance.

Concerns specifically related to capturing carbon dioxide include: "the cost of deployment, the scale of deployment, perceived risk (local health and safety), lack of accessible information, the need for supporting policies and the adequacy of supporting frameworks", although the extent of concern and implications varied among stakeholder groups (Ashworth et al., 2015, p. 449). These authors also noted that when CCS is compared with other low emission technologies, public credibility is dependent on two pre-conditions, the belief that climate change is a critical problem and the need for substantial carbon dioxide emissions reductions.

The proximity of CCS projects also affects acceptance, with some studies finding a "not in my back yard" (NIMBY) effect (Braun, 2017), although cross-country differences emerged with the UK slightly more accepting of CCS than other countries (Broecks et al., 2021; Whitmarsh et al., 2019). More recent research (e.g., Tcvetkov et al., 2019) has discussed how public acceptance of CCS is influenced by a complex interplay of factors, including trust in regulatory authorities, perceived benefits of carbon reduction, and the trade-offs inherent in risk–benefit evaluations. The application of established theories such as cultural cognition frameworks (Kahan, 2012), clarifies that emotional responses, trust deficits, and cultural values substantially shape these perceptions.

A few studies investigated public perceptions of CCS where pipelines specifically are used to carry carbon dioxide. In a small survey ($n = 139$), in Switzerland, Wallquist et al. (2012) investigated public acceptance of the type of plant where carbon dioxide is captured, type of pipeline, and type of storage. Their study applied a conjoint analysis experiment that allowed respondents to appraise the characteristics of the various elements of CCS systems simultaneously, rather than as single elements in isolation. Twelve CCS scenarios were presented to respondents to rate for acceptability. Wallquist et al. (2012) reported that pipelines (60%), type of plant (27%) and storage location (11%) scored the highest in importance. Pipelines showed a NIMBY effect as the Swiss respondents did not want a pipeline near their homes. Nonetheless carbon dioxide pipelines were preferred to those carrying gas. However, the usefulness of this research is limited by the small, non-representative sample size.

Research in the UK used deliberative focus groups to examine citizens' responses to the prospect of transporting carbon dioxide in a pipeline routed near their locality (Gough & Mander, 2014). Gough & Mander explored what UK citizens know about the properties of carbon dioxide and their key concerns about transporting carbon dioxide in pipelines. Using data from 19 small village participants, they concluded that, as with findings from previous studies, participants had a reasonable level of general knowledge about carbon dioxide but a poor understanding of its specific properties. These focus group participants also had little prior knowledge of CCS processes. Regarding the use of pipelines for transporting carbon dioxide, participants were highly sceptical and questioned the motivations behind pipeline construction. The participants voiced a lack of trust in the ability of institutions to control and regulate pipelines or CCS processes. Other concerns related to safety, disruption, impact on the environment, and a burden on local infrastructure. Despite these concerns, overall, the participants were not openly opposed to the prospect of transporting carbon dioxide in pipelines.

Another qualitative study in the UK explored stakeholder's perceptions of off-shore and on-shore carbon dioxide storage. Mabon et al., (2015) observed that public and stakeholder engagement with CCS is dependent on people's ability to connect their environmental experiences to appropriate analogues. However, Mabon et al., (2015) warn that even though environmental experiences can help conceptualise and rationalise abstract ideas, this embedded prior knowledge can also lead to a cautious stance towards CCS due to misremembered or mis-interpreted associations. Mabon et al., (2015) also found participants in their study were not always able to distinguish between the physical aspects of on-shore processes and off-shore risks. Although qualitative research is useful for understanding how and why opinions are formed, the small number of participants involved in these types of studies is unrepresentative of the wider UK population.

Research in Germany used a thousand telephone interviews to determine public perceptions of carbon dioxide pipelines (Schumann, 2017). Schumann found Germans have very low knowledge of pipelines and only 17% knew of the existence of pipelines to carry carbon dioxide in other parts of the world. The participants were asked their opinions on personal and societal risk, and their willingness to actively protest carbon dioxide pipelines routed near their homes. Since the results of the Likert scale questions were only slightly above neutral Schumann concluded, “on average carbon dioxide pipelines are perceived neutrally by the general public in Germany” (p. 7356). Measuring attitudes with a Likert scale, however, runs the risk of inaccurate reporting due to respondents interpreting the scales differently (Babin et al., 2020).

Parallel to developments in environmental risk research, advances in consumer research have introduced powerful tools for examining public attitudes that help to overcome framing effects common in social science. Studies by Carlisle et al. (2020) and Wright et al. (2014) have successfully employed cognitive association measures to capture the underlying mental models that drive consumer perceptions of proposals to mitigate climate change impact. The present study adds Best-worst scaling, a trade-off method developed in marketing and economics that reveals implicit preferences through repeated comparisons. These methods allow for a quantitative assessment of how specific attributes of proposed interventions, such as regulatory frameworks and transport methods, influence public acceptance. By integrating insights from both environmental risk theory and consumer research methodologies, the present study offers a systematic quantification of public perceptions and preferences for transporting carbon dioxide for CCS using a large-scale UK sample. This interdisciplinary approach not only solidifies the theoretical underpinnings of our work but also provides practical implications for policymakers and industry stakeholders seeking to enhance public engagement with decarbonization strategies.

In summary, while a growing body of work has examined public perceptions of CCS, few studies have simultaneously considered perceptions and preferences across the full chain of implementation, particularly for transport and temporary storage at ports. Research to date has often focused on individual components or relied on small samples, limiting generalisability and the ability to draw policy-relevant conclusions. Building on this foundation, the present study contributes by applying two complementary approaches—cognitive association measures and best-worst scaling—to a representative UK sample. These methods allow us to identify the dominant attributes associated with carbon dioxide transport and storage, and to evaluate public preferences among alternative implementation scenarios. In doing so, we provide a systematic and policy-relevant account of public responses to CCS and transport that can inform both the design of infrastructure and strategies for public engagement.

3 Methods

To investigate public perceptions of CCS transport and storage, we applied two complementary methods commonly used in consumer research: cognitive association measurement and best–worst scaling. These approaches were chosen to minimise framing effects and to capture both underlying perceptions and relative preferences. Figure 1 provides a schematic overview of the final research design, showing the sequence from participant recruitment through warm-up tasks, cognitive association measurement, and the best–worst scaling exercises.

After completion of the warm up questions, we applied methods developed in branding research (Romaniuk, 2013) to identify respondent cognitive associations (memory structures) for transport and storage of carbon dioxide at ports. The method is founded on the

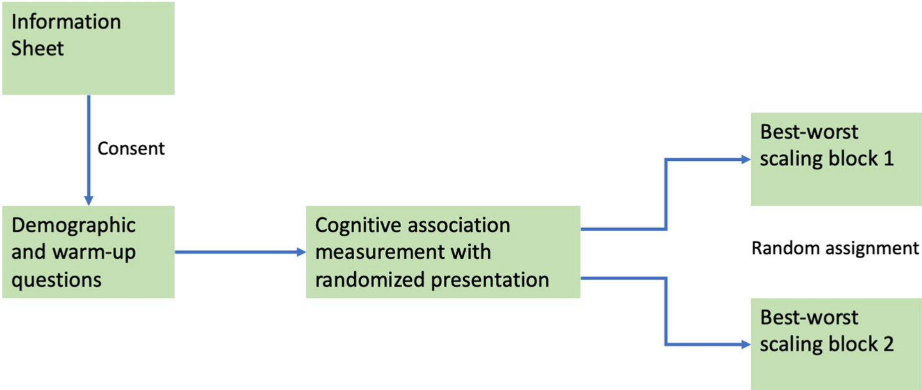


Fig. 1 Flow diagram illustrating participant progression from information sheet to demographic and warm up questions, cognitive association measurement, and finally Best-worst scaling tasks

cognitive processes of encoding, storing, and retrieving terms associated with objects, as described in associative network theory of memory (ANTM) (Anderson & Bower, 1974; Bettman, 1979). Memory constructs are evoked and measured by asking an individual which attributes they associate with a particular object, product, or technology. Making comparisons between similar technologies allows a relative assessment that controls for baseline response tendencies within the sample. The resulting memory associations can be analysed in a variety of ways, including as mental market share in a branding context (total share of associations), net positive/negative associations in the context of emerging technologies (where negative associations may be common, unlike a branding context), and through maps of associations that compare actual with expected levels of associations (i.e. controlling for size effects arising from the popularity of the concept and the popularity of the attribute).

The approach minimises response bias by eliciting memory associations rather than evaluative judgements, and minimises method bias and framing effects by commencing with warm-up questions to activate the relevant cognitive networks, randomising the order of presentation of the descriptors used, ensuring descriptors are matched on content, length, and use of positive and negative statements, and ensuring descriptors do not include the attributes used for evaluation. It has previously been extended to public engagement with science and emerging technologies, and the stability since found in results across countries and time periods is evidence of the method's robustness and suitability for evaluate public perceptions of emerging climate-related technologies (Wright et al., 2014; Carlisle et al., 2020, 2022, 2023).

Next, we applied Best-worst scaling, a method commonly used to measure consumer preferences, to alternative implementations of CCS and temporary storage. Best-worst scaling is based on random utility theory (Louviere et al., 2015) and overcomes the weakness of attitude scales that assume all people use the same evaluation rule when choosing among options. The procedure involves asking respondents to make repeated evaluations from groups (choice sets) of alternatives (profiles) to identify the best and worst alternative in the group. The profiles and choice sets are developed using experimental design procedures to simplify respondent choice tasks and allows valid statistical inferences.

Best-worst scaling Case 1 ranks a series of single attribute profiles. After eliciting evaluations from the presentation of multiple groups of attributes, a score for each attribute is derived by subtracting the number of 'worst' evaluations from the number of 'best' evaluations, with the results indexed to a value of 100 for the most preferred attribute to facilitate comparisons. Best-worst scaling Case 3 examines multi-attribute profiles, consisting of multiple factors for each profile each of which can take multiple values (levels). Ranks are derived as for Best-worst scaling Case 1 and then used as inputs to ordinal regression to identify the relative preference (utility) for each factor level, as well as the relative importance of the factors based on the magnitude of the utility variations within each factor (Flynn & Marley, 2014.)

3.1 Sampling and ethical considerations

The research was evaluated through peer review and assessed as low risk, and therefore was notified to the Human Ethics Committee but did not require further review according to the policies of the host University. The research proceeded through two stages of data collection using online surveys implemented through the Qualtrics survey platform. Participants drawn from the UK public using the commercial provider Dynata (https://www.dynata.com/). Respondents were presented with an information sheet that invited them to complete a survey on environmental technologies, assured that participation was voluntary and anonymous, given information on human ethics procedures together with researcher contact information, and then invited to consent by proceeding through the survey.

We used quota sampling to match the characteristics of the general UK population (see Appendix B). After screening out incomplete or inattentive responses, the final usable sample was $n = 1070$, yielding a maximum standard error of 0.015 on proportion questions. This is equivalent to a margin of error of +/- 3% at the 95% confidence level.

3.2 Procedures and materials

To select attributes for the main study, we developed a list of 30 candidate attributes from content analysis of previously published literature, including attribute elicitation carried out in other similar studies (Carlisle et al., 2020: 2022: 2023; Feetham, 2016; Wright et al., 2014). Respondents in the pilot study were given a brief description for several comparable industrial cryogenic substances that may be present at ports, including carbon dioxide, and then asked to select the attributes they associated with shipping and temporary storage of this substance at ports.

To select factors for Best-worst scaling 3 for the main study, we identified nine major types of decisions about the design of carbon dioxide capture, transport, and storage options, from relevant literature, and confirmed this list with an expert scientist familiar with CCS and transportation. Respondents in the pilot study were presented with groups of these decisions using Best-worst scaling Case 1 to determine those most important to the UK public.

In the main study, participants who agreed to participate were asked to provide demographic information and then introduced to the general topic of transport and storage of carbon dioxide. To warm-up participants and activate relevant memory structures, respondents were asked whether they agreed or disagreed with several questions related to CCS and transport using a five-point Likert scale.

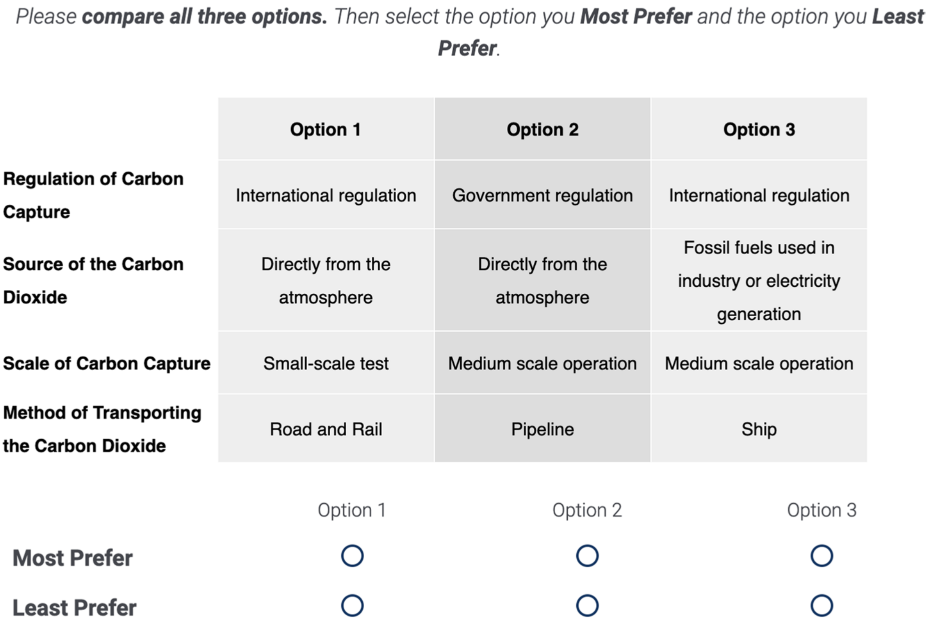
Following these introductory and warm-up activities, participants were introduced to the main task of cognitive association measurement of words that could be associated with transport and storage at ports of different industrial substances. This was followed by randomised presentation of both descriptors and attribute associations for carbon dioxide, hydrogen, ammonia and LNG. Following prior practice, the descriptors were matched on content, length, and use of positive and negative statements, while avoiding use of attributes selected for evaluation (Appendix A). Fourteen attributes were selected from the 30 appraised in the pilot study, with the final attributes used being balanced between positive and negative attributes and including: *Reduces emissions*, *Practical*, *Controllable*, *Dangerous*, *Sustainable*, *Understandable*, *Environmentally friendly*, *Unpredictable*, *Unfamiliar*, *Unproven*, *Controversial*, *Expensive*, *Safe*, *Unhealthy.*

We gathered and analysed respondent evaluations of the studied industrial substances using four metrics. These were: prior awareness of the transport and storage of these substances, popularity of the individual attributes indicating which dominate thinking in this context, net positive (or negative) associations showing the likely overall cognitive evaluation for each option, and concept maps showing individual variations from underlying association rates that provide additional interpretive value for each substance.

Following completion of the cognitive associations, participants were introduced to the Best-worst scaling 3 task requiring choices between different options for shipping and temporary storage at ports of carbon dioxide. Four factors identified from the pilot study analysis were selected (see below for further discussion of this selection): *Regulation*, *Source*, *Scale*, and *Transport*. These were further divided into three mutually exclusive levels for each factor to allow detailed comparison of policy options. The final factor levels were international regulation, government regulation, or industry self-regulation; transport by pipeline, ship, or road and rail; use of carbon captured from the atmosphere, plant material used to produce biofuels or electricity, or fossil fuels used in industry or electricity generation, and; from a small-scale operation, medium-scale test, or large-scale industry. See 4.0 Results and *4.4 Best-worst scaling* for further details of the pilot study results.

Having four factors of 3 levels each gives $3 \times 3 \times 3 \times 3 = 81$ possible factor-level combinations (profiles). Therefore, we applied standard simplification procedures to reduce respondent cognitive burden to a manageable level. These included generating a fractional factorial design using SPSS Orthoplan (Orthogonal Main Effect Plan or OMEP) to select just 9 out of the 81 possible profiles for study, and then applying a Balanced Incomplete Block Design (BIBD) to generate 12 sequential choice sets of three profiles each to be shown to respondents. Figure 2 provides an example of the task faced by participants for an individual choice set containing three profiles.

To further reduce the likelihood of respondent fatigue, the 12 choice sets were split into two balanced blocks of six choice sets each. Respondents were randomly allocated to either block and the presentation of choice sets was also randomised to avoid order effects. Although the complexity of the factorial designs used in Best-worst scaling case 3 means that blocking is common, it requires the assumption of homogeneity among respondents and so allows analysis solely at aggregate and not at individual or sub-group level.



*Please **compare all three options.** Then select the option you **Most Prefer** and the option you **Least Prefer**.*

	Option 1	Option 2	Option 3
Regulation of Carbon Capture	International regulation	Government regulation	International regulation
Source of the Carbon Dioxide	Directly from the atmosphere	Directly from the atmosphere	Fossil fuels used in industry or electricity generation
Scale of Carbon Capture	Small-scale test	Medium scale operation	Medium scale operation
Method of Transporting the Carbon Dioxide	Road and Rail	Pipeline	Ship

	Option 1	Option 2	Option 3
Most Prefer	○	○	○
Least Prefer	○	○	○

Fig. 2 An example of a choice set with three profiles used in Best-worst scaling Case 3

4 Results

Pilot data was collected in June 2022 with the main survey data obtained in August and September 2022. After data cleaning for incomplete, speeding, inattentive and nonsensical respondents, $n = 139$ responses remained in the pilot sample and $n = 1070$ respondents in the main sample. A comparison of sample demographic characteristics against UK population data demonstrates a very close match, with only minuscule skews in main study sample for the youngest and oldest age groups (Appendix B). The data is therefore appropriate for further analysis and for generalising conclusions about public perceptions.

Four questions were used to provide initial activation of respondent memory networks, and three of these were directly relevant to the studied topic. Results for these are as follows. 73% of the sample agreed that removing carbon dioxide from the atmosphere will help reduce global warming with only 5% disagreeing. Just over half of the respondents agreed that scientists and engineers have developed methods to capture carbon dioxide safely with only 5% disagreeing. Almost half of the sample agreed pipelines are a safe way to transport carbon dioxide but 6% disagreed (Table 1).

4.1 Cognitive association measurement

Prior awareness of shipping and temporary port storage was low to moderate, with 15–35% of respondents reporting having heard of each of the four substances in that context. LNG had the highest rate of awareness (35%), followed by hydrogen and carbon dioxide (23% and 21% respectively) while ammonia was the least familiar (15%).

Table 1 Warm up questions on attitudes to CCS and transport (%): respondents generally agree that removing carbon dioxide from the atmosphere will help reduce global warming. Around half agreed pipelines are a safe way to transport carbon dioxide and that scientists and engineers have developed methods to capture carbon dioxide safely. Standard errors are in provided parentheses

Statement	Agree	Neutral	Disagree	Don't know
Removing carbon dioxide from the atmosphere will help reduce global warming	73 (1)	13 (1)	5 (1)	9 (1)
Pipelines are a safe way to transport carbon dioxide	48 (2)	23 (1)	6 (1)	23 (1)
Scientists and engineers have developed methods to capture carbon dioxide safely	52 (2)	23 (1)	5 (1)	20 (1)

As noted, following the pilot study, fourteen salient attributes were selected for inclusion in the main study, balanced equally between positive and negative terms. After main study data collection, diagnostic tests were applied to determine the presence of intercorrelations between attribute associations. No substantive intercorrelations were found so all attributes were retained for further analysis.

Overall, positive attributes were more salient than negative attributes, indicating that public perceptions towards shipping and temporary port storage of the four substances are generally positive. The three positive attributes *Reduces Emissions*, *Practical*, and *Controllable* were the most popular accounting for nearly a third of all associations, whereas only one of the seven negative attributes, *Dangerous*, ranked in the top seven most popular attributes. (Fig. 3.)

	Attribute	CO2	Hydrogen	Ammonia	LNG	Average
1	Red. Emissions	10%	11%	8%	10%	10%
2	Practical	9%	9%	7%	13%	9%
3	Controllable	9%	8%	7%	12%	9%
4	Dangerous	6%	10%	12%	6%	8%
5	Sustainable	7%	9%	5%	8%	7%
6	Understandable	8%	7%	5%	9%	7%
7	Env. friendly	7%	9%	4%	8%	7%
8	Unpredictable	6%	8%	9%	5%	7%
9	Unfamiliar	7%	6%	9%	6%	7%
10	Unproven	8%	6%	9%	4%	7%
11	Controversial	6%	6%	9%	5%	6%
12	Expensive	7%	7%	5%	6%	6%
13	Safe	7%	5%	4%	8%	6%
14	Unhealthy	4%	2%	6%	2%	3%

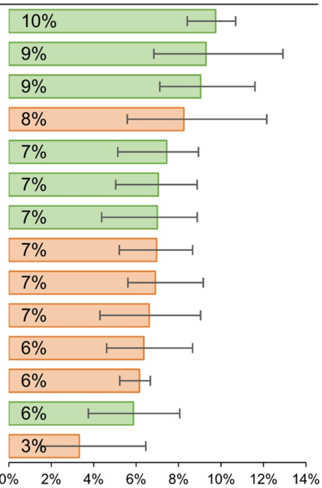


Fig. 3 Attribute associations by substance: The cells show the share of all associations for each attribute within each substance. The bars show the share of all associations for each attribute across all substances. The error bars show the range in share of associations between substances. Positively worded attributes (green) predominate over negatively worded attributes (orange). The maximum standard error for individual cells is 1% point

Interestingly, while *Dangerous* is the sole negative attribute to rank in the top seven, *Safe* was the only positive attribute to rank in the lower half, indicating the relative danger or safety of each fuel is of distinctive importance to the public. As near antonyms, these attributes may be thought to tap into a single underlying construct; however, they were not substantively correlated in our data, so were perceived independently in this sample.

The error bars in Fig. 3 show substantial variation in attribute popularity between the four substances. In particular, the attribute associations for *Dangerous* and *Practical* both vary by six to seven% points, indicating distinct differences in perceptions between substances, further explored in the following sections.

To examine perceptions and compare them between substances, we subtract the percentage of negative associations from the percentage of positive associations to produce a 'net-association' metric, like the net favourability metric sometimes seen in political polling. At the aggregate level, respondents' perceptions of transporting the four industrial substances evaluated are somewhat positive with 11% more positive associations than negative associations, indicating mild support toward shipping and temporary storage of industrial substances at ports. However, there are substantial differences in perceptions between the four industrial substances. LNG has the most positive associations, with 34% net positive associations. Perceptions of carbon dioxide and hydrogen are both 14% net positive, indicating somewhat positive perceptions. Ammonia is the only net negative substance with 19% more negative than positive associations. The results align with previous research on four alternative shipping fuels: Carlisle et al. (2023) that found that, amongst other results, hydrogen was the most preferred alternative marine fuel at 14% (net positive), LNG was also well-regarded 10% (net positive), whereas ammonia was the least preferred at −40% (net negative). (Fig. 4.)

Analysis at the disaggregate level of concept maps is also useful. A chi-square test confirms that individual attribute associations do vary between substances X^2 (39, N=13063)=767, p<.001 (note that N in this case is the total number of associations given by all respondents). To understand why perceptions of each substance differ, we calculate the percentage difference between actual and expected counts for each attribute and map them for each substance (Fig. 5). This approach removes baseline associations across substances, so the remaining values reflect the differences in public perceptions between each substance for each attri-

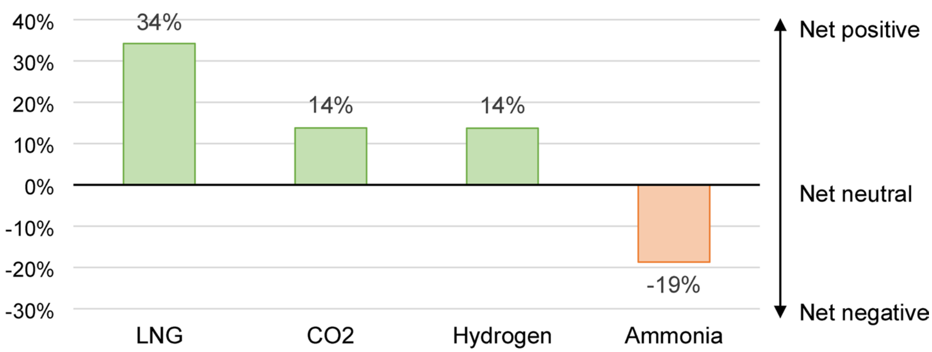


Fig. 4 Net associations for each substance (positive associations minus negative associations): Perceptions of LNG are strongly net positive, followed by carbon dioxide and hydrogen, whereas perceptions of ammonia are net negative. The maximum standard error of the estimates is 2% points; differences between substance of 4% or more are significant at the 95% confidence interval

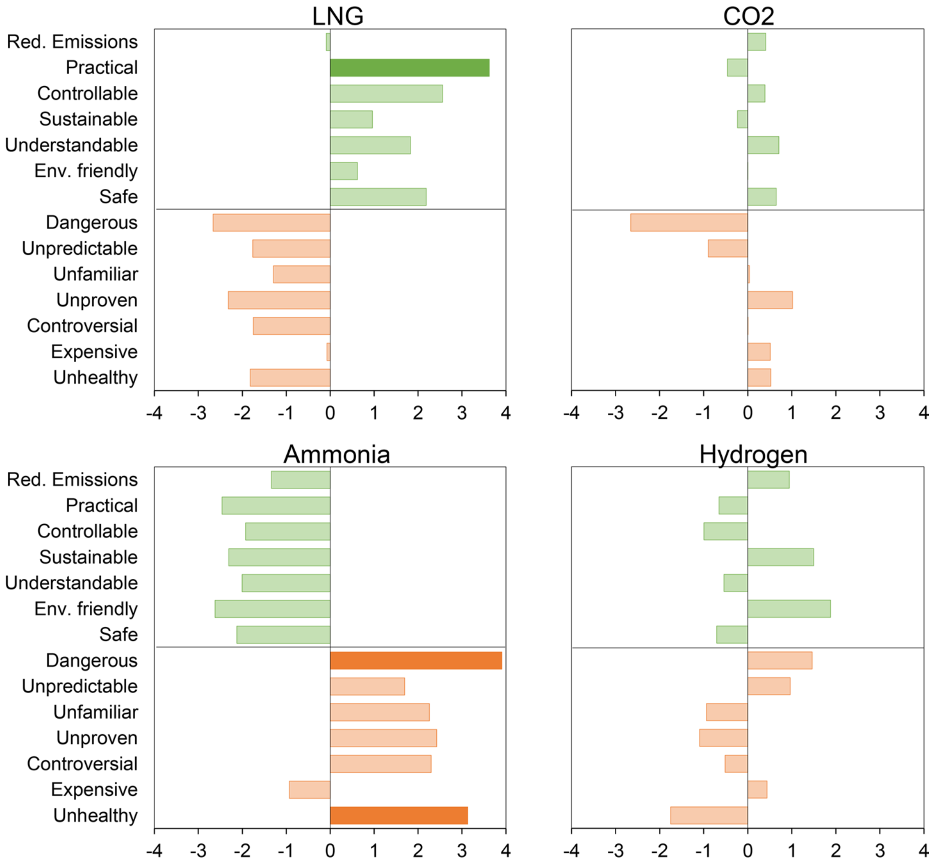


Fig. 5 Concept maps for the four substances show how attribute associations skew against the baseline expectation for different substances: Positively worded attributes (green) and negatively worded attributes (orange) are presented in descending order of popularity. Bars show the percentage point deviations between actual and expected attribute associations for each substance. Net positively perceived substances like LNG have higher than expected associations with positive attributes, and lower than expected associations with negative attributes. Negatively perceived substances like ammonia show the opposite pattern

bute after controlling for underlying attribute association rates. Individual concept maps are important for understanding the extent that overall public perceptions of specific substance are due to specific attribute associations.

The concept maps (Fig. 5) show that LNG is the most favourably perceived substance with more positive associations and fewer negative associations than expected, whereas ammonia is the least favourably perceived substance with the opposite characteristics. This pattern is typical of this form of analysis (Carlisle et al., 2020, 2022, 2023; Romaniuk, 2013; Wright et al., 2014) and aligns with findings in risk literature that people tend to see more benefits and fewer risks in activities they like, and vice versa (Slovic & Peters, 2006).

Although carbon dioxide and hydrogen are both somewhat favourably perceived, their deviations are predominantly small and irregular. Again, this pattern is known and is characteristic of relatively indistinct concepts (Romaniuk, 2013) for which public perceptions are likely to be relatively innocuous.

None of the deviations exceed the ±5% threshold often used to identify noteworthy deviations (Carlisle et al., 2023), indicating none of the substances are particularly distinctive, beyond eliciting a general preference. However, if the threshold is reduced to ±3% deviations, a few somewhat noteworthy observations are uncovered (Fig. 5: dark fill).

- LNG shows high rates of association with the positive attribute *practical* (3.6% more than expected), indicating the public view shipping and storing LNG as a moderately practical activity. This is perhaps unsurprising given LNG is a more familiar commodity to the public, with the highest rates of prior awareness (35% of participants).
- Ammonia, by contrast had moderately high rates of association with the negative attributes *Dangerous* (3.9% more than expected), and *Unhealthy* (3.1% more than expected). Again, this is unsurprising due to ammonia's toxic characteristics and poor image (Carlisle et al., 2023). On all seven positive attributes ammonia skews away from the baseline performing worse than expected.
- Carbon dioxide and hydrogen, by contrast, have no deviations exceeding ±3%, however, carbon dioxide does have somewhat low rates of association with the negative attribute *Dangerous* (−2.7% lower than expected) indicating the public perceive carbon dioxide as somewhat benign in the context of shipping and temporary storage at ports.

4.2 Best-Worst scaling

The pilot study applied Best-worst scaling Case 1 to reveal implicit rankings of nine potential decisions that could affect implementation of CCS and transport. The most important factors were *Regulation*, industrial *Source* and *Scale*, followed by another four factors with relatively low differences in relative importance: *Carbon dioxide use* (storage or industrial application), *Transport method* (pipeline, shipping, or road and rail), *Geographical source*, and *Transport form* (gaseous, liquid, or solid). A further two factors *Destination* (Storage in the UK versus export) and *Port storage* showed minimal impact on respondent decision making. We selected *Transport method* (hereafter *Transport*) as the fourth factor as prior literature emphasises this attribute, and it matched the objectives of the present study. It was not possible to include five or more factors as the complexity of factorial designs rapidly increases with additional elements.

As noted, each factor was then divided into three levels, giving $3 \times 3 \times 3 \times 3 = 81$ possible combinations. Application of OMEP and BIBD experimental design procedures resulted in the selection of 9 out of the 81 possible profiles, presented in 12 choice sets of three profiles each for the main study, and further divided into two response blocks to reduce respondent fatigue. Although participants were randomly assigned to either block, after data cleaning the number of respondents in each block was unequal with final sample sizes of $n = 548$ and $n = 522$. Therefore, 26 respondents were randomly removed from the first block to ensure all options appeared an equal number of times in the data used for analysis, satisfying the inferential assumptions of the experimental design. The data was then converted into relative importance rankings for all 9 profiles using Best-worst scaling Case 1 (Fig. 6).

The most preferred profile of those assessed is the combination of government regulation, carbon captured from the atmosphere, medium scale operation and transportation by

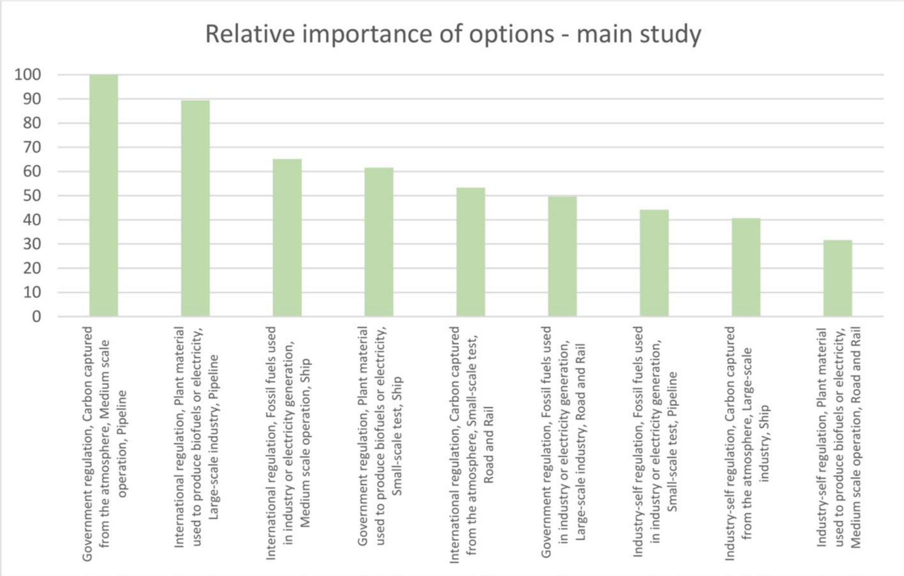


Fig. 6 Best-worst scaling results showing the relative importance of each choice profile: Profile descriptions are provided underneath each bar

pipeline. A close second preferred profile was the combination of international regulation, plant material used to produce biofuels and electricity, large-scale industry and transportation by pipeline. Two further profiles, first of international regulation, fossil fuels used in industry or electricity generation, medium-scale operation and transportation by ship, and second of government regulation, plant material used to produce biofuels or electricity, small-scale test and transportation by ship, are slightly more preferred than the subsequent four profiles. The least preferred profile is the combination of industry self-regulation, plant materials used to produce biofuels or electricity, medium scale operation and transportation by road and rail.

We applied ordinal regression to these ranks to derive utilities for each factor-level combination, completing Best-worst scaling Case 3 (Table 2). Utility measures are made relative to a baseline, so a negative score does not mean a factor is not preferred; it merely indicates that it is less preferred than other factors. Further, as utilities are relative measures, they have meaning within the specific set of experimental data obtained rather than through comparison between independent studies. The use of response blocking precludes calculation of standard errors in ordinal regression as responses must be aggregated to form a single population estimate.

The range of utilities within a factor indicate the relative importance of that factor to differences in preferences, revealing *Regulation* and *Transport* to be the most important factors and confirming the decision to include *Transport* in the main study. The *Scale* of the CCS and transport operation and the *Source* of carbon dioxide have much lower variation in utilities, and therefore less impact on the UK public's preferences on CCS and transport, than do *Regulation* and *Transport*.

Table 2 Utility scores from Best-worst scaling: the most important factors with greatest variation in utility scores are regulation followed by Transport. The largest differences in individual utilities are for international regulation (preferred) and industry self-regulation (not preferred) and transport via pipeline (preferred) and transport via road and rail (not preferred)

Factor	Level	Utility Score
Regulation	International regulation	1.67
	Government regulation	1.33
	Industry self-regulation	−3
Transport	Pipeline	1.67
	Ship	0
	Road and Rail	−1.67
Source	Carbon captured from the atmosphere	0.33
	Plant material used to produce biofuels or electricity	0
	Fossil fuels used in industry or electricity generation	−0.33
Scale	Medium-scale test	0.67
	Small-scale operation	−0.33
	Large-scale industry	−0.33

Utility scores for individual factor levels reflect the impact of each on CCS and transport preferences. For *Transport*, the scores of 1.67 for pipelines, zero ship, and − 1.67 for road and rail show that each will have markedly different value to the UK public. As *Transport* of carbon dioxide by pipeline has the highest utility among the transport levels, it will most positively influence CCS and transport preferences.

For *Regulation*, the scores of 1.67 for international regulation, 1.33 for government regulation and − 3 for industry self-regulation indicates the UK public will not be receptive to industry controlling CCS and transport. Instead, the UK public are more likely to accept CCS and transport governed by international or government regulators.

For *Source*, the utility levels show low magnitude and little variation between levels at 0.33, 0 and − 0.33, indicate commensurately less influence on preferences. For *Scale*, there is similar low magnitude and variation, although a medium-scale operation is slightly more preferred at 0.67 to small-scale testing (−0.33) and large-scale industry (−0.33). Small-scale operations score slightly higher than medium and large-scale operations but overall scores for this factor are low indicating its low influence in the trade-off decision. (Table 2.)

The most preferred profile overall is international regulation of pipelines carrying carbon captured from the atmosphere in medium-scale tests. The least preferred profile overall is international regulation of road and rail transport of carbon captured from fossil fuels used in industry or electricity generation for large-scale industry.

5 Discussion

Taken together, the results suggest that public reaction to CCS transport and temporary storage at ports is likely to be moderate, suggesting broad acceptability and a reduced risk of public opposition, particularly if industry self-regulation is avoided. The use of pipelines and either international or government regulation will increase the chances of public acceptance, although local objections may still arise in response to specific infrastructure projects as is common with public works. These patterns set the stage for more detailed consideration of individual attributes, transport modes, and regulatory preferences, discussed below.

5.1 Prior awareness and uncertainty

Consistent with earlier research on CO_2 (Tcvetkov et al., 2019) prior awareness of the four industrial substances in the context of shipping and temporary port storage is low to moderate at 15–35%. More respondents knew about LNG (35%) than hydrogen (23%) and carbon dioxide (21%), and relatively fewer knew of ammonia (15%) even though it is a major commodity transported globally. On the question of transportation of carbon dioxide by pipelines some uncertainty was evident. While almost half agree it is safe (48%) and few disagree (6%), many hold either a neutral view (23%) or answered don't know (23%). The combination of low awareness of the shipping and temporary port storage of industrial substances, together with the high levels of respondents who are neutral or unsure about transporting carbon dioxide by pipeline, suggests that a substantial knowledge gap exists in the UK public. This knowledge gap may need careful management during public engagement, as low prior awareness may create scope for development of risk perceptions. When developing CCS and transport, it may be helpful to emphasise to the public the long history of shipping and temporary port storage of other industrial substances and hidden success of numerous pipelines carrying essential commodities across industrialised societies.

5.2 Popular attributes and overall benefit perceptions across substances

The attributes most associated with a set of concepts provide an indication of the memory structures likely to be activated by similar kinds of stimuli. In the case of shipping and temporary port storage of selected industrial substances, the most popular attributes were *Reduces emissions*, *Practical* and *Controllable*, accounting for nearly a third of the total associations. As these are all positive attributes, they represent benefit perceptions that may predispose the UK public to accept transport and storage of industrial substances such as CO_2 through ports. Further, as these attributes are those that come to mind most easily, they ought to be included in public engagement efforts as this will increase the chances that relevant communications will be noticed.

5.3 Risk perceptions of individual attributes by substances

The concept maps provide more details on how risk perceptions varying across the four substances (Fig. 5), reporting the percentage point skews, or deviations, from expected values (Fig. 5).

Carbon dioxide's concept image is indistinct as the skews are small. Carbon dioxide has less than expected associations with the attribute *Dangerous* and is not considered *Unpredictable*. Given its indistinctiveness, public reaction to shipping and temporary port storage of carbon dioxide is likely to be more subdued compared to other substances such as ammonia.

Similarly, hydrogen reported insignificant skews, although it performed slightly better than expected on the positive attributes *Reduces Emissions*, *Sustainable*, *Environmentally friendly*, *Dangerous*, and *Unpredictable*. Shipping and temporary port storage of hydrogen is also unlikely to cause a major negative reaction from the UK public.

LNG has the most positive number of associations, and the most distinctive image of the four industrial substances evaluated. LNG's associations with the attribute *practical* are

3.6% higher than expected. However, given it is a commodity product and that 35% of the public were aware of this substance its concept image is not surprising. Of the four industrial substances evaluated for shipping and temporary port storage, LNG is likely to cause the least concern or reaction from the UK public.

Conversely, shipping, and temporary port storage of ammonia is the most likely to cause a strong negative reaction from the UK public. The concept image for ammonia shows higher than expected associations with the attributes *Dangerous* (3.9% more than expected) and *Unhealthy* (3.1% more than expected). On all seven positive attributes ammonia skews away from the expected baseline demonstrating the extent of negativity towards shipping it or holding it in temporary port storage. These findings also align with previous research on alternative shipping fuels that found ammonia was perceived as 'dangerous', 'toxic', 'hazardous', and 'poisonous' (Carlisle et al., 2023).

Individually, the four industrial substances are perceived quite differently. However, when carbon dioxide is compared to three other industrial substances currently shipped and temporarily stored at ports, the prevalence of positive attribute associations indicates a majority of the UK public are unlikely to react negatively towards its shipping or temporary storage in ports. Risk perceptions for carbon dioxide are not high, particularly in comparison to ammonia.

5.4 Trust

The Best-worst scaling results identify Regulation as one of the most important factors affecting respondent preferences, with large differences between international regulation or government regulation and industry self-regulation. The implication of these preferences is that the UK public has less trust in industry self-regulation that in the other options. Given that trust has been repeatedly identified as a key factor affecting CCS acceptance, the findings imply that policymakers should prioritise government or international oversight mechanisms in the design of CCS frameworks to maintain public trust. Industry stakeholders may need to collaborate with third-party regulators to increase credibility.

5.5 Summary

Key findings and their immediate implications for communication and engagement are summarised in Table 3. These implications form the evidentiary base for the more specific policy recommendations developed in the following section.

6 Policy implications

Building on the summary provided above we now distil the results into broader policy recommendations. The following subsections draw together the contents of Table 3 into subject-specific guidance for regulators and infrastructure planners.

Table 3 Summary of key findings: the results provide many findings to inform policy development and public consultation

Topic	Finding	Implication
Removing atmospheric carbon dioxides helps reduce global warming	A large majority agreed (73%), only 5% disagreed.	Policymakers and communicators should emphasise the climate mitigation role of CO_2 removal and emissions reductions, as these enjoy strong baseline support.
Scientists and engineers have developed safe methods for CCS	Half agreed and 5% disagreed	Where scepticism exists, stakeholders should proactively communicate safety protocols and technological maturity to reinforce public confidence.
Pipelines are safe for carrying carbon dioxide	48% agreed, 6% disagreed and 23% neutral.	Communications and consultation should highlight pipeline safety records and precedents, targeting the significant neutral and undecided segment.
Prior awareness of shipping & temporary port storage (CO_2, LNG, H_2, NH_3)	Carbon dioxide 21%. All substances low-moderate 15–35%.	Public engagement strategies should include information about existing practices to close knowledge gaps and reduce novelty-related concerns.
Perceptions of transporting substances.	11% net positive. *Reduces emissions*, *Practical*, *Controllable*, dominate	Messaging should emphasise positive associations to increase receptivity, while addressing risk perceptions (e.g., "dangerous") directly and transparently.
Perceptions of transporting Carbon dioxide	14% net positive associations, (same as hydrogen). Less than LNG at (35% net positive).	Policymakers can proceed with moderate confidence, but avoid complacency around new or unfamiliar infrastructure.
Important factors for CCS & transport	*Regulation* and *Transport* more influential than *Source* and *Scale*. Pipelines, government/international regulation preferred	Regulatory design should prioritise public trust; infrastructure planning should favour pipeline transport where feasible and socially acceptable.
Most preferred CCS & transport option	Government regulation, CO_2 from the atmosphere, medium scale, pipeline	This configuration should be prioritised in consultation materials and project design to maximise acceptance.
Second most preferred CCS & transport option	International regulation, bio-based CO_2, large-scale, pipeline	This profile is also acceptable; it may be emphasised in contexts where international coordination or bio-based sources are more salient.
Most preferred options for regulating CCS	International regulation has higher utility (1.67), than government (1.33) or industry self-reg (−3)	Policymakers should favour international or government regulation. Industry stakeholders should partner with trusted public agencies to increase legitimacy.
Most preferred options for transporting CO_2	Transporting by pipeline has higher utility (1.67) than ship (0) or road and rail (−1.67)	Infrastructure developers can consider pipelines. Use road and rail cautiously.

6.1 Prioritise trusted regulatory frameworks

Public confidence in CCS hinges on who regulates it. Our findings show strong preferences for international and government oversight, with industry self-regulation comparatively poorly received. Policy should therefore mandate independent oversight mechanisms and clearly define the roles of government and supranational bodies in CCS governance.

6.2 Emphasise pipeline infrastructure as the default option

Pipeline transport received the highest levels of support, both in general perceptions and in revealed preferences. Road and rail transport options were less acceptable. Policymakers should consider pipeline corridors in infrastructure planning and environmental assessment, and prefer shipping where pipelines are impractical.

6.3 Address safety perceptions proactively

While CCS technologies are considered safe by many respondents, a sizeable neutral group remains uncertain about pipeline safety. Regulations and policy documents should explicitly reference international safety records, incident monitoring systems, and transparent reporting to reduce this uncertainty.

6.4 Integrate public engagement into siting and scale decisions

Preferences varied across source and scale dimensions, with medium-scale projects and atmospheric or bio-based CO_2 generally favoured. Future siting and scaling decisions should incorporate early consultation, especially in communities directly affected by pipeline routes, extraction sites, or port facilities.

6.5 Communicate climate mitigation benefits clearly

A strong majority agreed that CCS provided a solution to mitigate anthropogenic global warming. Policy documents and public consultations should highlight the contribution of CCS to net zero pathways, balancing this positive framing with transparent acknowledgment of risks.

7 Conclusion

UK public perceptions of CCS transport and temporary storage at ports are largely positive. 73% of the sample agreed that removing carbon dioxide from the atmosphere will help reduce global warming and 52% agreed that scientists and engineers have developed methods to capture carbon dioxide safely. Since the purpose of CCS is to capture source emissions and remove atmospheric carbon dioxide, these perceptions likely have a positive influence on the acceptability of CCS. Respondents showed more positive than negative associations with CCS and transport, leading to a favourable net positive association score. When compared with three other industrial substances, the net positive score for CCS and transport was equal to that for hydrogen and greater than that for ammonia. In considering how CCS and transport could be implemented, Best-worst scaling revealed that *Regulation* and *Transport* were the more important factors of those evaluated. Respondent choices revealed implicit preferences for government regulation rather than industry self-regulation, and for transportation by pipeline.

Together, these results suggest that the social licence for CCS in the UK is attainable. At the same time, the results highlight several areas where knowledge gaps and uncertainties could affect long-term acceptance. Future research exploring how different communication approaches, regulatory frameworks, and localised infrastructure proposals interact with public memory structures will be important to ensuring the successful rollout of CCS infrastructure. Insights from such research will help ensure that specific implementation strategies remain not only technically sound but socially acceptable and publicly supported.

While this research systematically quantifies the perceptions of carbon capture, storage and transport in the UK, there is much scope for additional theoretical, methodological and empirical work. Some promising avenues for future research are detailed below.

The successful application of memory association measures to chemical substances demonstrates the method's flexibility and robustness. This methodology could be readily extended to representative samples in other countries to measure global public perceptions of CCS to inform policy and industry decisions. Future studies could expand the approach through alternative comparator substances and technologies, or simplified Best-worst scaling designs that enable individual-level modelling and more granular analysis.

Research could also explore how cognitive association patterns vary across demographic groups. Theoretically grounded subgroup analyses examining factors such as education, location, or income could reveal whether and how these characteristics shape cognitive memory structures related to CCS. Given challenges around data sparsity and multiple comparisons, such investigations would require larger, purpose-designed samples specifically measuring demographic effects on associative memory formation and retrieval.

Perceptions may vary for other contextual reasons, such as between different port locations, different countries, or for specific pipeline routes (including through private land). Public opinion in localised areas could suffer a NIMBY effect and vary from the perceptions of CCS and transport held more generally. As a further point for future research, it would be helpful to understand the factors that might lead to a Yes-in-my-backyard (YIMBY) effect as opposed to a NIMBY effect.

Our quantitative approach does not address how perceptions form or what interventions might shift them. Similarly, we provide limited insight into how institutional discussions might unfold within affected communities - including deliberations between local councils, community groups, industry representatives, and broader social media discourse. Understanding these dynamic processes represents a important complement to the baseline perceptions documented here and may require other kinds of qualitative research approaches.

As a final point, we know from memory theory that elicited perceptions may change depending on the stimuli. While memory structures underlying public perceptions are quite robust, the elicitation of associations depends on the stimuli used. Our work controls for differences in stimuli to avoid any framing effects and ensure comparisons between methods are unbiased. However, public discourse, particularly when led by perceived to be trusted sources, may preferentially elicit certain memory structures rather than others, possibly leading to priming or bandwagon effects that could shape ongoing reactions. It would be useful to conduct research to understand how different communication strategies and source credibility levels influence memory structure activation, and to what extent repeated exposure to particular framings can then create shifts in public perceptions.

Appendix

Appendix A. Question wording for industrial substances attribute associations

Now, we are going to ask what you think about the transport and storage at ports of four different industrial substances

On the following pages we will show you information about the transport and storage at ports of four different industrial substances. Each of these substances could potentially play a role in reducing greenhouse gas emissions. In this part of the research, we are trying to find out the words that you associate with the description of each substance. So please read the descriptions and then select as many words as you think might apply.

Industrial substance: Carbon Dioxide

To reduce greenhouse gas concentrations in the atmosphere, scientists think that carbon dioxide could be captured from industrial sources and stored underground. As part of this process, some carbon dioxide would need to be transported and temporarily stored at ports in large tanks. Carbon dioxide is a naturally occurring gas that traps heat in the Earth's atmosphere. Human activity also releases carbon dioxide and so contributes to rising global temperatures. Carbon dioxide gas is non-flammable but can cause asphyxiation (lack of oxygen) if inhaled in high concentrations. However, the risk of leakage is low. Carbon dioxide will be shipped as a supercooled pressurised liquid.

Please read the description and then select as many words as you think might apply to shipping and temporary storage of carbon dioxide at ports

< followed by the list of fourteen attribute descriptors ending with 'None of these'>.

Industrial substance: Hydrogen

To reduce greenhouse gas concentrations in the atmosphere, scientists think that Hydrogen could be used as an alternative fuel to replace fossil fuels. As part of this process, hydrogen would be transported and temporarily stored at ports in large tanks. Hydrogen is already used in a variety of industrial processes and could be used as a low-emission alternative fuel if produced using renewable energy. Hydrogen gas rarely occurs naturally because it reacts with oxygen in the air to form water. Hydrogen is unscented and very flammable. However, the risk of leakage is low. Hydrogen will be shipped at ambient temperature as a pressurised liquid.

Please read the description and then select as many words as you think might apply to shipping and temporary storage of hydrogen at ports

< followed by the list of fourteen attribute descriptors ending with 'None of these'>.

Industrial substance: Ammonia

To reduce greenhouse gas concentrations in the atmosphere, scientists think that ammonia could be used as an alternative fuel to replace fossil fuels. As part of this process, ammonia would be transported and temporarily stored at ports in large tanks. Ammonia is already used in a variety of industrial processes and could be used as a low-emission alternative fuel if produced using renewable energy. Ammonia can occur naturally, but is produced by industrial processes. Ammonia is corrosive and toxic. However, the risk of leakage is low. Ammonia will be shipped at ambient temperature as a pressurised liquid.

Please read the description and then select as many words as you think might apply to shipping and temporary storage of ammonia at ports

< followed by the list of fourteen attribute descriptors ending with 'None of these'>.

Industrial substance: Liquified Natural Gas

To reduce greenhouse gas concentrations in the atmosphere, scientists think that Liquified Natural Gas (LNG) could be used more widely as an alternative fuel to replace other fossil fuels. As part of this process, LNG would be transported and temporarily stored at ports in large tanks. LNG is commonly used as a relatively clean fossil fuel for heating and cooking. LNG is produced industrially by refining and cooling natural gas into a liquid state. Natural gas is flammable. However, the risk of leakage is low. LNG will be shipped at ambient temperature as a pressurised liquid.

Please read the description and then select as many words as you think might apply to shipping and temporary storage of Liquified Natural Gas at ports

<followed by the list of fourteen attribute descriptors ending with 'None of these'>.

Appendix B. Comparison of sample demographics and UK population

	Population Estimate (ONS*, 2020)	Pilot Sample ($n=139$)	Quantitative Sample ($n=1070$)
	%	%	%
England	84	85	84
Wales	5	1	5
Scotland	8	12	8
Northern Ireland	3	2	3
Age (Years)			
18–24	13	2	10
25–34	18	16	17
35–44	19	20	19
45–54	19	19	18
55–64	16	17	16
65–74	12	24	11
75–80	5	2	7
Gender			
Male	49	46	49
Female	51	54	51
Gender Diverse	-	0	<0.1
Other	-	0	<0.1
Prefer not to say	-	0	<0.1
Population			
Less than 200 people (Rural Area)		4	4
200 to 999 people		7	6
1,000 to 9,999 people		19	14
10,000 to 49,999 people		21	21
50,000 to 99,999 people		12	16
100,000 to 999,999 people		22	24

	Population Estimate (ONS*, 2020)	Pilot Sample (n=139)	Quantitative Sample (n=1070)
1 million to 4.9 million people		6	6
More than 5 million people (Major Urban Area)		7	10

* Office for National Statistics.

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Data availability Data will be made available on reasonable request.

Declarations

Competing interests The authors declare no competing interests.

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