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Lay perceptions of Carbon Dioxide Utilisation technologies in the United Kingdom and Germany: An exploratory qualitative interview study

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Published version

JONES, Christopher R., OLFE-KRAEUTLEIN, Barbara and KAKLAMANOU, Daphne (2017). Lay perceptions of Carbon Dioxide Utilisation technologies in the United Kingdom and Germany: An exploratory qualitative interview study. Energy Research & Social Science, 34, 283-293.

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Abstract

Carbon Dioxide Utilisation (CDU) technologies convert Carbon Dioxide (CO_2) into carbon-based products. CDU technologies are viewed as a means of helping to address climate change while creating commodities that can be sold to generate financial revenue. While technical research and development into CDU options is accelerating, at present there has been little research into public acceptance of the technology. The current study presents the findings of a series of 28 exploratory interviews conducted with lay people in the United Kingdom and Germany. The results show that awareness of CDU is currently very low in both countries but that there is tentative support for the concept. This support is, however, caveated by considerations of the techno-economic feasibility of the technology and the societal consequences that might result from investment. While the thematic content of discussions was similar in both countries, where appropriate any notable differences are outlined and discussed. In addition to providing fresh insight into the emerging nature of public perceptions and acceptance of CDU, it is reasoned that the findings of this research could help to benefit the design of communication materials intended to engage lay-publics in debate about the nature and purpose of CDU technologies.

Keywords

Carbon Dioxide Utilisation (CDU); Carbon Capture and Utilisation (CCU); Public Perception; Technology Acceptance

1. Introduction

Carbon Dioxide Utilisation (CDU) technologies—also often referred to as Carbon Capture and Utilisation (CCU) or Carbon Capture and Reuse (CCR) technologies—convert Carbon Dioxide (CO_2) via physical or chemical processes into saleable carbon-based products (e.g. polymers, methanol). By making use of waste CO_2 released by large point-source emitters (e.g. fossil-fuel power generation, steel manufacture, etc.) or directly from the air; CDU technologies are viewed as a means of helping to address climate change—consistent with emerging national and international policy and legislation (e.g. that precipitating from the 'Paris Agreement' at COP21, see United Nations Framework Convention on Climate Change, 2015)—while broadening the raw material base and creating commodity products (e.g. chemicals, plastics, cement, fuels, urea) that can be sold to generate economic revenue (Styring, Quadrelli & Armstrong, 2015).

The concept of CDU is not new and there are already mature markets for CO_2-based products like urea and sodium carbonate; however, there is growing interest in a variety of new CDU options, including CO_2-derived fuels (e.g. methanol, formic acid) and other chemicals (e.g. acyclic carbonate, polyurethanes), which still remain at various stages of research, demonstration and feasibility testing (Fraga & Ng, 2015; Wilson et al., 2015). Crucially, while technical advancement of these options is accelerating, there is currently little research into the public (and broader social) acceptability of the technologies and related product options (see Jones, Olfe-Kraütlein, Naims & Armstrong, 2017).

The present study used exploratory semi-structured interviews in order to learn more about the nature of emerging lay-public opinions of the technology in the United Kingdom (UK) and Germany. There was a particular focus on the anticipated conceptual, techno-

economic and societal risks and benefits of the technology (see Jones et al., 2015). The UK and Germany present a particularly interesting context for such investigation in Europe, due to their prominent and advanced technical CDU research and development programmes (Mennicken, Janz & Roth, 2016; SCOT, 2017; SETIS, 2016).

The remainder of this introduction first outlines the importance of studying the public acceptance of technological innovation (Section 1.1), before summarizing what is currently known about public perceptions of CDU (Section 1.2). It ends by outlining the specific aims and objectives for the current study (Section 1.3).

1.1 Public acceptance of technological innovation

The key role that lay-publics (e.g. in their roles as voting citizens and product consumers) have in shaping the success of technological innovation at national, local and household levels (e.g. prospects for investment, the ability to find sites, etc.) (Devine-Wright, 2011; Wüstenhagen, Wolsink & Bürer, 2007; Upham, Oltra & Boso, 2015), has led to calls for earlier and more participatory engagement of such publics in discussions regarding technological and policy innovation (Chopyak, 2002; Kurath & Gisler, 2009; Jones & Jones, 2016; Wilsdon & Willis, 2004).

This is of particular importance within Westernised democracies, where policy and institutional change typically requires the support of individuals and communities (Peterson, Stevens & Wilson, 2015). Indeed, there are a number of instances where failures within public engagement and deliberation have led—at least in part—to delays or curtailments to the introduction of new technologies at both national (e.g. *GM agriculture*, e.g. Horlick-Jones et al., 2007) and local levels (e.g. *renewable energy technologies*, e.g. Devine-Wright, 2011).

If correctly resourced and planned, such engagement activity can yield benefits for

proponents of a given innovation (Beierle & Cayford, 2002; Creighton, 2005). Timely and meaningful engagement *can* for instance: (a) generate public trust in decision-makers and promote acceptance (or tolerance) of decisions; and (b) yield key insight into the emerging subjective perceptions of the technology (e.g. the perceived risks and benefits), which can make a substantive contribution to decisions being made about the technology (see Stirling, 2008). For example, expert and lay judgments about the type and severity of risk posed by hazards (including new technologies) can deviate markedly from one another (Sjöberg, 2015). By engaging with affected publics it can be possible to identify areas of divergence, which can be useful in designing tailored education and communication strategies (Lee, 2016).

As an example, social scientific research into the lay-public perceptions of Carbon Capture and Storage (CCS) is now fairly mature. CCS technologies capture CO_2 emissions from large point-source emitters (e.g. power plants), allowing for the transportation of the CO_2 to deep-geological storage sites (e.g. depleted oil and gas fields) (Boot-Handford et al., 2014; Gibbins & Chalmers, 2008). The social scientific studies that have been conducted to date have yielded key insight into attitudes towards the technology among diverse publics (e.g. affected populations, nationally representative samples) and other stakeholders in a number of countries (Johnsson, Reiner, Itaoka, & Herzog, 2010; Shackley et al., 2007; Upham & Roberts, 2011). In addition to identifying some of the perceived risks and benefits of CCS (see L'Orange Seigo et al., 2014), this research has provided a basis for the creation of public-engagement programmes and communication materials designed to prompt more informed discussion about the processes and principles of the technology (Ashworth et al., 2012; Ashworth, Boughen, Mayhew, & Millar, 2010; Brunsting et al., 2011).

In short, while the 'public face' of technological innovation is often an afterthought (see Apt & Fischhoff, 2006); elucidating and integrating the opinion of lay-publics (alongside those of other social-stakeholders) into technological design, development and deployment should be considered a priority.

1.2 Public perception of Carbon Dioxide Utilisation (CDU)

Due to the conceptual and semantic overlaps between CCS and CDU—and the fact that CDU can be affiliated with CCS operations (Markewitz et al., 2012; Styring et al., 2015)—it could be tempting to draw inferences about the probable lay-public response to CDU from the extant literature on CCS. There are, however, limitations to this, not least due to the inherent differences in the nature and intended purpose of these technologies.

The *raison d'être* of CCS is to combat climate change and thus public perceptions of CCS are strongly determined by beliefs in anthropogenic climate change and the perceived utility of CCS in combating this threat (L'Orange Seigo et al., 2014; Wallquist et al., 2012). While CDU *can* also result in net reductions in CO_2 emissions, the prospect of also creating products and generating economic revenue provides a secondary purpose for investment in the technology. Furthermore, as CDU does not necessitate the geological storage of CO_2—a commonly registered grievance with CCS—it is reasonable to hypothesise that attitudes towards CDU might differ from those held about CCS (Bruhn, Naims & Olfe-Kräutlein, 2016).

While still at an early stage, initial attempts at conducting systematic assessments of lay-public perceptions of CDU technologies and product options are beginning to emerge (e.g. Jones, Kaklamanou, Stuttard, Radford & Burley, 2015; Perdan, Jones & Azapagic, 2017; van Heek, Arning & Ziefle, 2017a, 2017b). For example, Jones et al. (2015) conducted

a focus group study with adults and high school children in the UK. In addition to confirming the low level of existing public awareness about CDU, the research highlighted some of the emerging themes in lay-public discourse about the technology. These themes centred on: (1) issues relating to the general concept ("*should we do this?*"); (2) technical issues ("*can we do this?*") and (3) societal consequences ("*what will happen if we do this?*"). More specifically, *concept* discussions focused principally on the value of CDU in addressing climate change. While some participants valued CDU as a means of 'buying time' in the fight against climate change, others questioned the efficacy of CDU as a long-term solution to the problem (e.g. due to the eventual re-release of the captured CO_2). *Technical* discussions tended to centre on concerns about the high capital-costs required to bring CDU technologies and products to market, as well as questions about the cost-effectiveness and thermodynamic efficiency of CO_2 conversion processes. In terms of *social consequences*, participants spoke about a range of issues, including perceived inconsistencies between investment in CDU and societal drives towards sustainability. For example, some viewed CDU as something that might encourage societal complacency in reducing carbon emissions, while others believed that CDU could be seen as a motivating exemplar of efforts being made to address this issue.

van Heek et al. (2017a) also recently published research into the antecedents of consumer perceptions for a CDU-derived mattress. In addition to confirming that participants tended to have relatively positive perceptions of CDU (particularly relative to storage of CO_2), the findings also confirmed a number of things about the factors that might govern the acceptance of consumer products derived from captured CO_2. For example, the proportion of CO_2 used within the product (*CO_2 proportion*) was not a particularly strong predictor of product acceptance. By contrast, both: (a) the carbon emissions affiliated with a CDU-derived

mattress upon disposal (*disposal conditions*); and (b) the extent of any fossil-resource savings resulting from the use of CO_2 as a carbon feedstock in the manufacturing process (*savings of fossil resources*), were predictive. Furthermore, where personal health risks (*perceived health complaints*) were introduced and considered by participants, it was these considerations that became the most decisive factor in shaping acceptance.

While most research in this area has, to date, been qualitative—appropriately recognising the challenges of assessing lay-public perceptions of unfamiliar subject matter (e.g. assessing *pseudo-opinions*, see Section 2.1)—recently larger, quantitative surveys have also begun to emerge. For instance, Perdan et al. (2017) conducted a survey on 1213 UK adults to establish the extent of awareness and acceptance of CDU (in this case referred to as CCU). This study illustrated the very low-level of public awareness about the technology (only 9% were confident they knew what the technology was); simultaneously highlighting both the challenge and opportunity for proponents of the technology in securing public acceptance.

1.3 The current study

While there is growing interest in understanding lay-public perceptions of CDU (and affiliated product options), there still exists a paucity of published research in this field (see Jones et al., 2017). The current study sought to address this gap by providing an exploratory investigation of opinions about CDU within a convenience sample of interviewees from the UK and Germany.

Twenty-eight in-depth, qualitative interviews were conducted with lay-people in Sheffield, United Kingdom (*n=18*) and Potsdam/Berlin, Germany (*n =10*) between July 2014 and December 2015. The aim was to elucidate more about emerging perceptions of CDU in

these countries, using the *concept*, *technical* and *societal consequence* themes identified to previous research as a framework for the analysis (see Jones et al., 2015).

Due to the fact that CDU facilities can be affiliated with CCS operations (e.g. Styring et al., 2015) we were also able to investigate how extant public opinion about CCS in each country shaped interviewee's opinions about CDU. We were particularly keen to see if the greater scepticism about CCS technologies in Germany relative to the UK—due to high social and political rejection of CCS technology in Germany (Herrenbrück, 2015; Johnsson, Reiner, Itaoka, & Herzog, 2010; Pietzner et al., 2011; Shackley et al., 2007)—would result in the German interviewees also being more sceptical towards CDU.

2. Methods

2.1 Qualitative interview approach

Individual qualitative interviewing was selected as the preferred method of data collection for this research. Qualitative interviewing offers a means of providing an in-depth, discursive forum for exploratory research and has been used successfully to discover more about the nature of expert and lay opinion of a number of emerging technologies, including CCS (Wallquist, Visschers & Siegrist, 2009); Geoengineering (Pidgeon et al., 2012); Hydrogen Energy Technology (Ricci, Bellaby, & Flynn, 2008) and Hydraulic Fracturing (Ladd, 2013). Bearing in mind the unfamiliar nature of CDU technologies, qualitative interviewing was favoured over other methods (e.g. a questionnaire-based survey) as a means of reducing the prospect of registering *pseudo-opinions*.

Pseudo-opinions are weak and non-directive evaluative judgements that people provide in responses to questions about things they know very little (if anything) about (de Best-Waldhober, Daamen, & Faaij, 2009). Qualitative interviewing ostensibly lessens the

prospect of recording pseudo-opinions by offering the opportunity to: (a) provide participants with more information about topic(s) under consideration; and (b) to clarify participants' understanding before eliciting opinion. The one-on-one context can also help to lessen the drawbacks associated with the more group-based discussion methods (e.g. *group think*, see Esser, 1998), which have also been a favoured means of investigating lay-public opinion of unfamiliar technologies like CCS (Bradbury et al., 2009; Hope & Jones, 2014; Upham & Roberts, 2011) and CDU (Jones et al., 2015).

2.2 Participants

Eighteen people from Sheffield (UK) and 10 people from Potsdam/Berlin (Germany) were recruited (see Table 1) to a study advertised as concerning *"…new technology options being developed to make use of the carbon dioxide produced by industrial processes, like electricity generation"*.[i] No prior knowledge of the technologies and/or power generation were required to participate. In the UK only, a small participation incentive (i.e. £20 shopping-voucher) was offered.

UK-based participants (8 female and 10 male) were recruited via an advertisement on a local online forum, an email advertisement to a University list of volunteers and via personal contacts. This recruitment strategy resulted in a slight overrepresentation of university research staff and students; however, a range of people from different backgrounds (e.g. lawyer, events manager) were also recruited. The sample had a mean age of 33.7 years (*SD* = 8.2; *Range*: 21-53). Five participants claimed to have heard of CDU but self-claimed pre-interview knowledge of CDU was very low (*Mean* = 1.11, *SD* = 0.32).[ii]

German-based participants (5 female and 5 male) were recruited via personal contacts. The final sample comprised people with a diversity of occupational backgrounds

(e.g. architect, secretary). The sample had a mean age of 44.8 years (*SD* =17.8; *Range*: 18-76). Four participants claimed to have heard of CDU but self-reported pre-interview knowledge of CDU was very low (*Mean* = 1.30, *SD* = 0.48).

Table 1.

Gender, age and occupation of the UK and German interviewees

Sheffield, United Kingdom
UK1 (M, 48, retired lawyer); **UK2** (F, 53, community carer); **UK3** (M, 38, computer programmer); **UK4** (M, 35, events manager); **UK5** (F, 36, learning support provider); **UK6** (F, 33, university researcher); **UK7** (M, 21, university student); **UK8** (F, 27, university student); **UK9** (M, 28, university researcher); **UK10** (F, 40, biomedical scientist); **UK11** (M, 29, research governance coordinator); **UK12** (M, 29, doctor); **UK13** (M, 36, university lecturer); **UK14** (F, 27, communications advisor); **UK15** (M, 30, project manager); **UK16** (M, 34, biotechnologist); **UK17** (F, 29, research developer); **UK18** (F, 23, library assistant).
Potsdam/Berlin, Germany
GER1 (F, 27, student); **GER2** (M, 39, teacher); **GER3** (F, 71, retired secretary); **GER4** (M, 76, retired civil servant); **GER5** (F, 53, accountant); **GER6** (F, 38, communications advisor); **GER7** (F, 42, occupational therapist); **GER8** (M, 18, student); **GER9** (M, 42, journalist); **GER10** (M, 42, architect).

Note. Gender (M = male; F = female); Age (years); Occupation (as listed by the interviewee)

While caution should be exercised due to small and discrepant nature of the sample sizes, initial comparative analysis indicated that the UK and German-based samples were

equivalent in terms of the mean age, $t(11.13) = 1.89$, $p = .088$, and pre-interview knowledge of CDU, $t(13.59) = 1.11$, $p = .289$. Fisher's exact tests (two-tailed) confirmed that the gender distribution ($p = 1.00$) and self-claimed awareness levels ($p = 0.67$) were also equivalent.

2.3 Materials

All materials were first created in English and then translated into German. Technical details were developed in collaboration with the UK Centre for Carbon Dioxide Utilisation (CDUUK) (www.sheffield.ac.uk/cduuk) and from previously published research (see Jones et al., 2015). For the exact wording of the information, see Appendix A.

2.3.1 Interview Information Sheet and CDU presentation

The information sheet outlined the reasons for the research, provided a brief background to CDU and introduced the data-management, analysis and ethical protocols. Participants also received a PowerPoint presentation comprising three key sections:

(A) General Introduction. This section outlined the names and roles of the research team, restated the project aims and provided a basic introduction to CDU (see Appendix A). When contextualizing CDU, discussion centred upon the need to address anthropogenic CO_2 emissions from large emitters like fossil-fuel power generation. Firstly, CCS was introduced as a possible means of sequestering CO_2, with the financial-cost, energy-cost and waste implications of this option outlined as potential drawbacks. Next, CDU was introduced as an option that could make use of *some* of the CO_2 from processes like CCS for enhanced oil recovery (EOR) or to make carbon-based products. In the context of product manufacture it was suggested that CDU could help to ease the reliance on new fossil fuels in the manufacture of these products and limit atmospheric releases of CO_2. Participants were then shown a diagram illustrating the variety of uses for captured CO_2 (see Figure 1). Participants

were told that electricity would be required to power the capture and conversion processes and that this electricity would have to come from renewables or other low carbon sources (e.g. nuclear power) to ensure that CDU processes yielded net reductions in CO_2 emissions. The diagram was available for participants to refer to during the *Question Set 1* (see Table 2).

(B) Specific Examples. This section showcased some case-study examples of CDU.[iii] Four CDU projects were briefly described: (1) German-based chemical-companies BASF and Covestro (formerly Bayer Material Science) and the US-based company Novomer capturing CO_2 and using chemical catalysis to convert it into plastics (e.g. polypropylene and polyurethane) for use in foams, adhesives and packaging; (2) the US-based Dakota Gasification Company's 'Great Plains Synfuels Plant' which captures and transports CO_2 from coal gasification for sequestering and use in EOR in Saskatchewan, Canada; (3) German car-manufacture Audi's 'e-gas' project, which is creating synthetic gas from CO_2 for use as transport fuel and as a potential replacement for natural gas in main gas lines; and (4) UK-based company Air Fuel Synthesis's project to synthesise kerosene from CO_2 sequestered via direct air capture processes.

(C) Expert ratings. This section comprised a table depicting elite assessments of CCS and six CDU options (e.g. plastics manufacture) rated against eight evaluative criteria (e.g. technology readiness level, profit potential). The expert ratings represented the modal estimations of a group of over 10 engineers and natural scientists with academic expertise in CDU processes and products, recruited via the CO2Chem network (www.co2chem.co.uk). For each evaluative criterion, higher ratings (max. 10) related to more favourable evaluations of the CDU/CCS option. This table was used to enable participants to consider and discuss the relative strengths and weaknesses of CCS and the different CDU options (see Jones,

Radford, Armstrong & Styring, 2014). For the table of expert ratings and the definitions of the evaluative criteria, see *Supplementary Material* (Table S1).

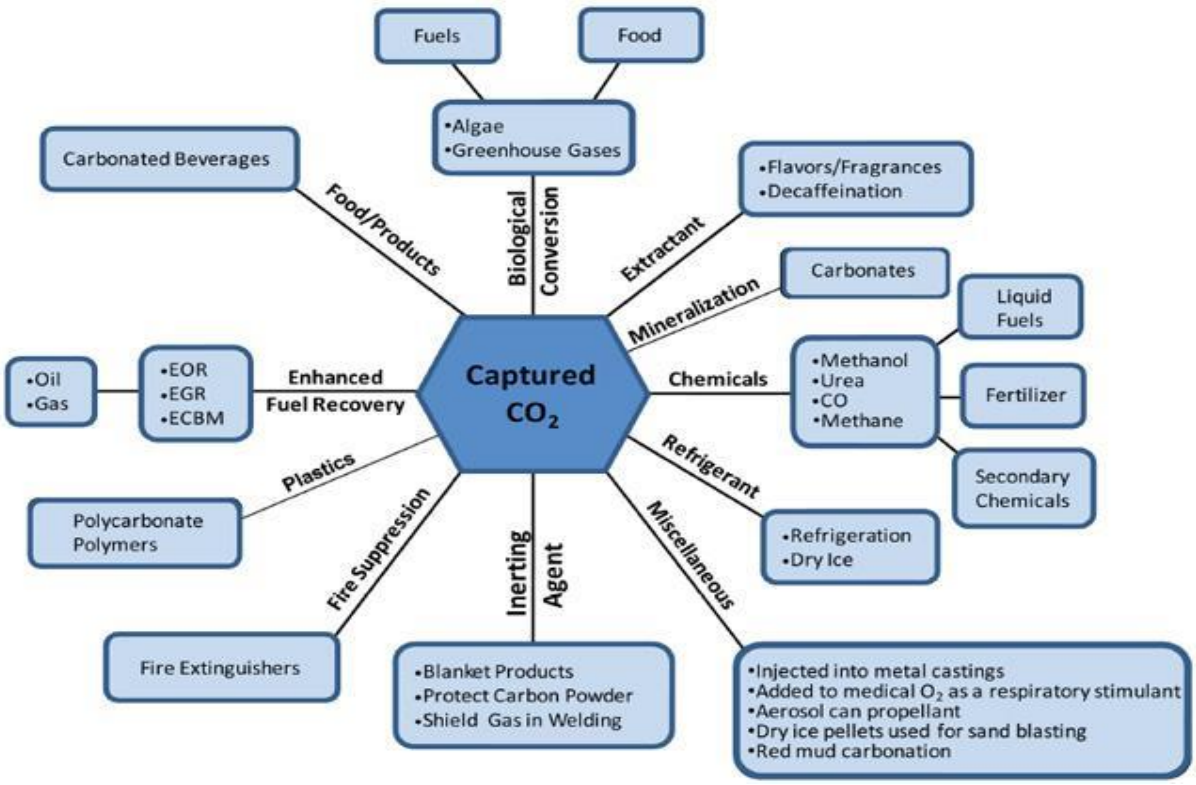

Fig. 1. Schematic diagram of use options for captured CO_2.

The diagram illustrates how CO_2 can be utilised as a resource, including options that are already used today (e.g. utilisation of CO_2 as a refrigerant), and products and processes of different readiness levels (e.g. polycarbonates). Source: U.S. National Energy Technology Laboratory (NETL). The figure is reproduced with the permission of the owner.

2.3.2 Pre-interview Questionnaire

This questionnaire was distributed before the interview and recorded the interviewees' age, gender and occupation (all free response), as well their initial self-claimed awareness

(*"Have you heard of…?"* Yes, No, Don't Know [DK]) and knowledge of (*"How much to do you think you know about…?"* Not a lot; A little, A fair amount; A lot) CDU.[iv]

2.4 Procedure

A representation of the interview procedure can be found in Figure 2. Interviews took place in a quiet, one-to-one setting, they were semi-structured and lasted between 30-60 minutes. UK interviews took place in October 2014 and German interviews took place between July and December 2015. All questions can be found in Table 2. Where relevant the interviewer asked the participant to clarify unclear statements and provide fuller explanations for their responses (see Wallquist et al., 2009).

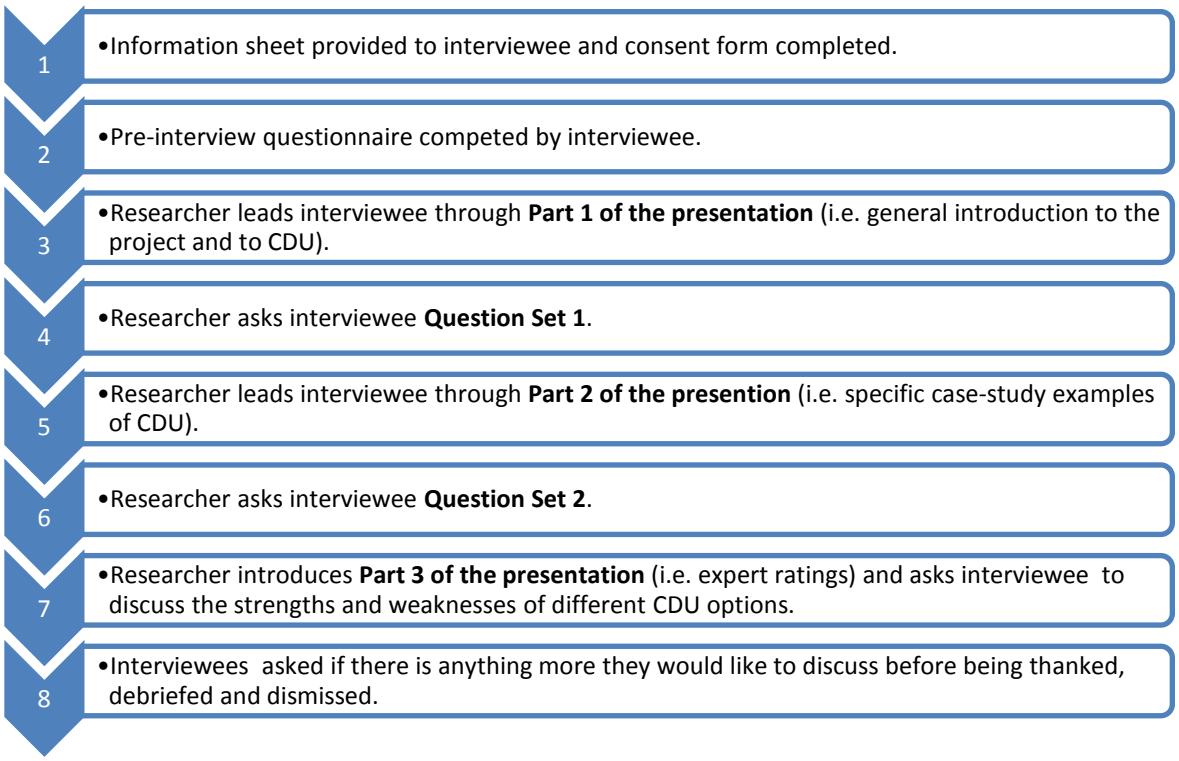

Fig. 2. Overview of the interview procedure.

Note: Interviewees also completed a short post-interview survey (at Step 8) but the results of this survey are not analysed further within the current study.

Table 2.

Question schedule for interviews (semi-structured)

Question Set 1	
1	Before today's session, how much did you know about CDU?
2	Has the information you have just received changed what you know about CDU?
3	Has the information you have received had an impact on how you feel about CDU and if so, in what way?
4	Do you think it is a reasonable technology for climate change mitigation?
5	Do you think it is a reasonable to technology for any other purposes?
6	What do you think are the general benefits of CDU technology?[1]
7	What do you think are the general risks of CDU technology?[1]
8	Is there a particular aspect of the process that you think is particularly risky?
Question Set 2:	
1	What would you think if a CDU pilot project was planned to be sited near to where you live?[2]
2	Generally speaking what role, if any, do you think CDU has within the UK/Germany?
3	To what extent do you think that CDU should or shouldn't be considered as a means of mitigating CO_2 emissions from industry?
4	To what extent do you feel that CDU should or shouldn't be considered as a solution for climate change?
5	Do you think CDU has more environmental benefits, more economic benefits or both?

Note: [1] Participants were probed for perceived effects on the climate, on future generations and on themselves. [2] Participants were probed for whether they though that this would be a

good or a bad thing.

2.5 Data analysis approach

Template Analysis was used to explore the data (see Brooks, McCluskey, Turley, & King, 2015). Coding centred on the perceived advantages and disadvantages of CDU in terms of: (a) the general concept (*"should we do this?"*); (b) its techno-economic feasibility (*"can we do this?"*); and (c) its consequences for society (*"what will happen if we do this?"*) (see Jones et al., 2015). 'Other' themes (e.g. comments about the interview procedure) were also recorded and coded. Preliminary data coding was conducted on the first UK interview (UK1) using these themes as a template. Modifications were made to the coding-template based upon this analysis. The revised coding-template was then applied to UK2 and UK3 and any further updates made. The revised coding-template was checked by all the authors before being applied to the remaining UK interviews. Where relevant, codes were added/revised and retrospectively applied to pre-coded transcripts. The final UK coding-template was then translated into German and applied to the 10 German transcripts. The coding-template is available within the *Supplementary Material* (Table S2).

UK interview transcripts were first coded by CJ (lead author), with the coding of a sub-sample of 3 transcripts independently checked by DK (co-author). German transcripts were first coded by BOK (co-author), with a sub-sample of 2 transcripts independently checked by a second, native German speaker. Any disagreements between coders were discussed, resolved and amendments applied to the coding of all transcripts.

3. Results

There were broad similarities in the opinions expressed within the German and UK

samples. As such, the results section comprises a joint presentation of the themes arising from these two groups; where appropriate notable differences between the cohorts are highlighted.

3.1 Comments on the CDU concept (*"should we do this?"*)

While there was some scepticism, interviewees were broadly supportive of the CDU concept. This positivity was, though, often conditional on the grounds that CDU should not be a sole focus for investment in tackling climate change. More specific conceptual discussions of CDU centred on 3 sub-themes: (1) the utility of CDU as a means of addressing climate change; (2) the consistency between CDU and the broader sustainability agenda; and (3) the comparative favourability of CDU vs. other technologies, particularly CCS.

3.1.1 The utility of CDU in addressing climate change

Some participants questioned whether CDU would provide a viable answer to the issue of climate change. Concerns mainly mapped to the belief that CDU would present an 'end-of-pipe' solution to carbon emissions and would not tackle their root causes.

"…[CDU] sounds as though it is a logical option compared to the storage [of CO_2], however, yes, it kind of raises questions as to whether it is focusing on the right end, is there a way that we can reduce the CO_2 that we produce in the first place?" UK14

Some interviewees also reasoned that CDU would only delay an inevitable release of CO_2 into the atmosphere and so would not hold longer-term benefits for tackling climate change. That said, interviewees recognised that not all CDU products were equivalent in this regard, with options offering more permanent CO_2 storage seen as more preferable.

Assumptions about the scale of the contribution that CDU could make to addressing climate change were also found to shape opinions. Where these benefits were considered nominal, the value of the technology was questioned. That said, while CDU was not

considered to be *the* solution to climate change, a number of interviewees noted that it could help to slow the problem or 'buy time' while more efficacious solutions were developed.

3.1.2 The consistency of CDU with the broader sustainability agenda

Some CDU products—notably plastics—were seen to conflict with societal drives towards greater sustainability. In the UK, some interviewees also believed that CDU would presuppose an unwelcome, continued use of fossil fuels as well as also being a risky technical fix for what are complex environmental issues.

Sceptical interviewees also indicated that they were unclear as to the rationale behind CDU, questioning whether the environmental motives were sincere or whether the rationale was primarily economic. This scepticism apparently stemmed from a lack of trust in the companies promoting the technology and led to calls among some German participants to monitor and regulate industrial practices and products in order to confirm any claims regarding environmental sustainability.

Alongside these more sceptical comments, however, participants also registered key strengths to CDU in terms of encouraging sustainability. Comments related to the belief that CDU would create a new 'recycled' carbon resource that could: (a) reduce raw resource consumption by industry; (b) maximise the potential yield from existing, 'activated' fossil fuels and replace their use in the manufacture of products; (c) advance innovation in science and industry; and (d) help to move society towards a more circular economy.

"I love the idea of a circular economy; the waste of one process is being used as a starting product for another. [CDU] is brilliant and totally fits into it, and really closes the carbon loop that we have in our society." UK16

3.1.3 The comparative favourability of CDU vs. other technologies.

German interviewees saw CDU to be a preferable option to CCS and responded negatively to the affiliation of CDU with CCS; rejecting this framing on the grounds that it did not allow for the consideration of CDU in the absence of CCS. In the UK, participants typically viewed CCS *with* CDU as being the more favourable option. This preference generally stemmed from the perceived risks and drawbacks with the underground storage of CO_2, with long-term storage was seen as wasteful, dirty or dangerous (e.g. from leakage or explosion). This contrasted with the view of utilisation as being akin to recycling.

"[CDU] seems a lot better than [CCS], like I said before, it's the difference between landfill, CCS being landfill, and CDU being more akin to recycling […] My reaction to CCS is generally that I don't like mess that you can't clean up properly." UK3

Some participants were concerned that a (re-)focusing of financial investment towards CDU could harm investment in other technologies (notably renewable energy technologies) that are perceptively more consistent with the sustainability agenda. Where this occurred, opinions of CDU were typically less favourable.

3.2 Techno-economic Comments (*"can we do this?"*)

Pragmatic considerations of technical and economic feasibility often caveated interviewees' positivity to the general CDU concept. While such pragmatism was often driven by a self-claimed lack of knowledge about the technology, it was also tied to the recognition that many CDU options were commercially unproven. Discussions broadly mapped to 2 sub-themes: (1) the technical feasibility and the CO_2-capture potential of CDU; and (ii) the commercialisation and market potential for CDU technologies and products.

3.2.1 The technical feasibility of CDU and CO_2-capture potential

Participants were generally uncertain as to the proportion of CO_2 that would be

utilised via CDU processes. Where participants believed that CDU could stand to capture large amounts of CO_2—and thus register a significant impact on carbon emissions—opinions were typically favourable. Some suggested that they would need more information regarding the capture potential and 'real world' benefit of the technology before they would be willing to support CDU.

For some participants, the early technology readiness and/or low market-penetration of some CDU options led them to question the immediacy of any discernible benefits that could be derived from CDU. Interviewees argued that it would be a long time before CDU operations were on a scale that could make a meaningful contribution to global issues, such as climate change. Moreover, it was believed that there would need to be significant international investment—particularly from developing nations—if CDU were to make a meaningful contribution to such issues.

"[I]t is getting people like China and India to get on board […] because they are so big that they can make a significant impact if they do it. But if they don't then the UK is just a fraction of the rest of the world, insignificant really in world terms" UK15

In both countries, some participants questioned whether the high energy-costs associated with the CDU conversion processes might undermine the worth of the technology and could lead to net increases in CO_2 emissions. This scepticism was, however, sometimes countered by the belief that financial investment in current CDU technologies could help to increase the viability of future technology options.

3.2.2 The commercialisation and market potential for CDU

There was general uncertainty over the costs involved in commercialising CDU and over the potential market for CDU technologies and products. It was appreciated that CDU

would have to make economic sense for investors, leading to speculation over how CDU facilities might be funded (e.g. would there be implications for consumers). That said, many participants did believe that making use of CO_2 could yield profit for investors (e.g. either directly or through reduced emissions taxes) and that CDU would be attractive to industry if it could generate a cheap carbon feedstock for products.

Participants in both countries alluded to a number of economic benefits for investors in CDU, reasoning that: (a) CDU and its products had the potential to integrate easily with extant industrial infrastructures and (diverse) markets; and (b) there would be future domestic and international retail markets for those investing in CDU technology research and development.

"…if you are a front runner in developing technology then you can export and become an expert in this at both exporting either the technology or setting up companies elsewhere feeding in, will be good for the UK economy in the long term." UK16

In the UK there was also a sense among a couple of interviewees that investment in CDU could be used to enhance business credibility for investors and/or encourage welcome investment in the renewables sector.

3.3 Societal Consequences (*"what will happen if we do this?"*)

Four key themes were identified: (1) the consequences of CDU for societal change; (2) the impact on consumers; (3) the public and environmental health and safety risks; and (4) the impacts on business and industry.

3.3.1 The consequences for societal change

Interviewees had differing views on whether investment in CDU would have positive or negative consequences for efforts to promote more sustainable lifestyles within society.

Specifically, some participants sensed that people might use the environmental credentials of CDU as an excuse for not living more sustainably, while others suggested that CDU could provide a catalyst for fostering change in both the public and business sectors.

Relatedly, some interviewees noted that countries like the UK and Germany would be setting a good example for other nations by investing in CDU, which could potentially catalyse positive change within these other countries.

"I think it could benefit the British economy actually because then it's something that ultimately we take out to, sort of, developing countries that are currently going on their industrial revolution and help making them more viable and cleaner and not damaging their own environment as well." UK9

3.3.2 Impacts on consumers

There was a sense that the costs associated with CDU could be quite high and would need to be 'picked up' by someone. It was argued that this could be end-consumers through inflations in the price of products, although some argued that this premium might not be an issue if it were relatively small, optional and/or if the environmental benefits of the products were clear.

"*I could imagine that, if not mandatory, people will be convinced quickly to do their bit out of an ecological awareness. For me personally, the ecological motivation to buy something would be bigger than the economical one*." GER2

Concern over the potential for inflation in the price of consumer products was not universal and the prospect that CDU might produce a low-cost source of carbon, which could reduce—or at least mitigate increases in—the cost of consumer products (e.g. transport fuel) was seen as a potential benefit.

3.3.3 Public and environmental health and safety risks

Interviewees' comments regarding health and safety issues tended to focus on the transportation and storage of captured but unused CO_2. Concerns principally mapped to the potential for leakage, explosion and related negative effects on local populations, flora and fauna. The utilisation of CO_2 was not seen as overly risky; although, there were occasional mentions of possible hazards from the chemicals used in the conversion processes and/or the chance of explosion or harmful emissions from these processes. Some participants also questioned if their might be unknown risks associated with CDU-derived products.

"I think that one should know what is inside things. I do not really like the thought of having a waste material in things that for example touch the skin, like creams or plastics in garments. I think the same about other materials, but with CO_2 even more." GER3

In Germany, trust in regulatory systems to protect consumer-welfare was found to increase the perceived safety of CDU-derived products. And some German interviewees were enthused by the symbolic ('badge of honour') prospect of using CO_2-derived products.

3.3.4 Impacts on business and industry

In both countries many comments mapped to beliefs about the use-value of CDU in creating products (e.g. fuels, plastics) and supporting businesses and industry. Moreover, within the UK, CDU was valued a non-disruptive technology option; i.e. something that could reduce industrial emissions while allowing society to operate and function as normal.

"This could kind of go on in the background. Every CO_2-producing power station could adopt this technology tomorrow and nobody would notice in terms of our day-to-day lives." UK7

Many interviewees valued captured-CO_2 both as a substitution feedstock for use in the

manufacture of carbon-based products and as something that could help to lessen the need for crude-oil imports, thereby fostering greater energy independence. The substitution potential of CDU-derived carbon (vs. traditionally-sourced carbon) was seen as particularly attractive within Germany, where some interviewees referenced the country's extant industry as providing a good basis for investment – provided there was a business case.

A few UK interviewees also commented on the potential employment opportunities that could be derived from the CDU industry, although there was some uncertainty over the number and longevity of such opportunities.

3.4 Other themes

Several prominent additional themes were raised through discussion, relating to: (1) public communication and engagement considerations; (2) facility siting and deployment considerations; and (3) comments on the interview procedure.

3.4.1 Public communication and engagement considerations

Participants from both countries noted the value for CDU proponents in engaging in early discussions about the technology. In part, these comments appeared to stem from the interviewees' personal concern that the success of the technology could be undermined by failures in public engagement. One UK participant spoke of the potential for the media to amplify perceptions of technological risk, using this to highlight the value of CDU proponents taking control over how the technology is framed and promoted.

"…the media like to make a big hoo-hah over it [new technology] and it scares people. Then people don't ever get facts and figures and real information. All they get is media scare…" UK6

Interestingly, some participants also argued that care should be taken when drawing

conclusions about the public acceptability of CDU from opinion polls or surveys. Drawing on their own lack of knowledge, they cautioned that the current low-level of public awareness about CDU might mean that surveys would record a surface-level endorsement of the technology, which might not translate into support for CDU when people learned more about the technology, its purpose and implications.

3.4.2 Project siting and deployment considerations

While the prospect of local facility development was typically not deemed of personal relevance, interviewees did note that there could be issues within communities where future CDU facilities were planned. This again raised the importance of public-engagement and careful site selection. Interviewees hypothesised that local resistance might form to proposals on the grounds of unwelcome noise and visual impacts, negative effects on house prices, construction disruption, and concern regarding the storage of captured CO_2.

Some concern was expressed where participants did entertain the prospect of development within their own community; however, this concern appeared to be tied to the prospect of local development *per se* as opposed to anything specific about the facility being involved in CDU.

"I generally do not want to have industrial plants built in my surroundings" GER4.

3.4.3 Comments on interview procedure

Interviewees typically reasoned that the information provided within the interview had improved their understanding of CDU and/or had had a positive influence on their attitudes. While most interviewees spoke freely within the interview, a number also registered a desire to have more 'facts and figures' (e.g. about the risks and economic costs) in order to further aid their understanding and/or confirm their beliefs about CDU.

"… I'd have to see the figures and the numbers, and things like that, before I could say, 'Yes, it's a really good idea', or 'No, this is a terrible'…" UK1.

4. General Discussion

Overall, interviewees tended to show a 'caveated acceptance' of CDU, which apparently stemmed largely from a self-claimed lack of knowledge about the technology and questions over the magnitude of the environmental benefit that could be derived from CDU. The fixation on the environmental benefits of CDU is logical bearing in mind the 'framing' used within this study, which was chosen to reflect the pro-environmental argumentation commonly used when discussing the technology (Palanivelu, 2017; Styring et al., 2015).

In addition to shaping conceptual-level discussions of CDU, the environmental framing also affected interviewees' consideration of the techno-economic feasibility and societal consequences of the technology. For instance, interviewees' comments regarding the early technology readiness level and CO_2 capture potential of CDU, can be taken as reflecting general concerns about the likelihood, scale and immediacy of any environmental benefits that might be derived from the technology. Similarly, comments relating to the realisation that investment in CDU would only occur if there was a good business case (e.g. from the retail of expertise, technologies and products and/or enhanced business reputation, see Karakosta, Doukas, & Psarras, 2010; Miles & Covin, 2000), could be seen to reflect concerns that the desirable environmental benefits from CDU might be stymied by the commercial unattractiveness of the technology. For an outline of some of the key questions and considerations apparently shaping interviewees' opinions of CDU, see Figure 3.

Interestingly, where there was scepticism about the environmental benefits of CDU, this tended to drive differing responses in the UK and German-based participants. In both

countries, trust in the sincerity of proponents of the technology was questioned; however, whereas German interviewees tended to call for the regulation of the CDU industry in order to validate the environmental credentials of processes and products (e.g. through labelling of consumer goods)[v], UK interviewees tended to call for CDU proponents to engage in a more honest re-framing of communications regarding the technology so as to recognise the financial motivations for investment. This latter finding strikes parallels with research into lay-public attitudes to CCS, indicating how publics have more trust in stakeholders when they use arguments that more consistent with their perceived organisational motives (de Vries, Terwel, Ellemers, & Daamen, 2015; Terwel, Harinck, Ellemers, & Daamen, 2011).

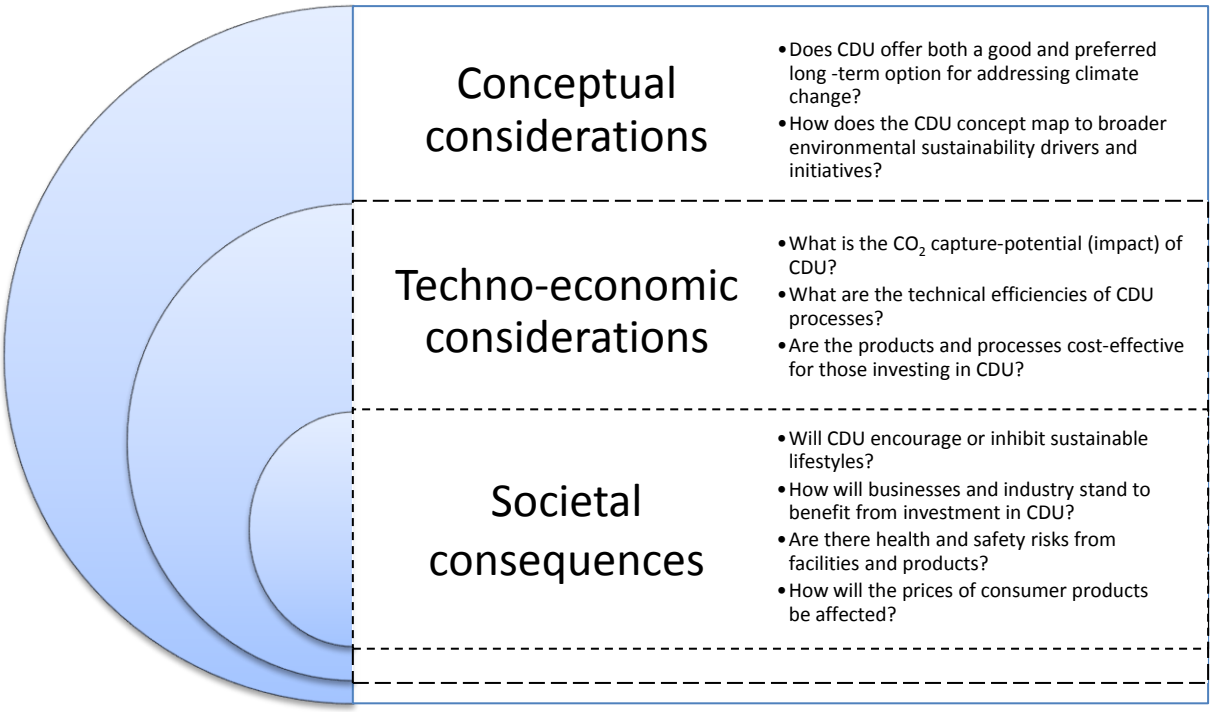

Fig. 3. Questions apparently driving perceptions of CDU

Conceptual consideration of the environmental advantage to be gained from investment in CDU tended to be focal (consistent with the framing utilised in this study) and was also found to largely underpin considerations of techno-economic viability and societal consequences.

4.1 Implications, limitations and future directions

The findings of this study present new insight into emerging lay-public perceptions of CDU technology. While exploratory in nature, we feel that the findings of this study could—in combination with the specific, growing literature on lay-perceptions of CDU from other sources (see Jones et al., 2017) and the established literature on the acceptance of new technologies (see Gupta, Fischer, & Frewer, 2012; Huijts, Molin, & Steg, 2012)—help to contribute to the development of communication materials designed to help prompt wider public debate about CDU. This move would be consistent with drives towards greater participation of publics in science and technology policy and decision making (see Chopyak, 2002; Kurath & Gisler, 2009) and consistent with similar efforts made in analogous technology sectors (e.g. CCS, Ashworth et al., 2010; Ashworth et al., 2012).

There are, however, some important limitations to this study that should be considered if seeking to utilise our findings for such purposes. Beyond the obvious limitations relating to the relatively small and opportunistic nature of our sample—which should be addressed in future research efforts (e.g. through more purposive sampling of interviewees)—there are other, more specific limitations relating to the nature and extent of the information provided to interviewees in this study.

In terms of the *nature* of the information provided, our chosen framing of CDU as a 'green' technology option was found to markedly shape interviewees' discussions of the technology (see Figure 3). In addition to steering discussion of the technology towards considerations of environmental impact, couching CDU in such terms arguably also framed the technology in a positive light. While there was certainly evidence that our interviewees were willing to discuss the drawbacks of the technology and while our semi-structured

interview format allowed us to probe both interviewees' negative and positive viewpoints; it is possible that our chosen framing was partly responsible for relatively positive opinions formed towards CDU within this study.

We feel that this limitation provides a real opportunity for future, systematic research into the nature of lay-public attitudes towards the technology. Numerous studies indicate how even subtle alterations to the framing of a technology (e.g. the emphasis placed upon the different attributes of a technology) can exert impacts on perceptions of the technology, particularly in comparative contexts and/or where technologies are unfamiliar (e.g. de Vries, Terwel & Ellemers, 2016; Druckman & Bolsen, 2011; Jones, Eiser, & Gamble, 2012). A logical first step in this research would be to investigate how interviewees might respond to discussions of CDU in a context where a more balanced picture of the technology is provided (e.g. where details about the environmental credentials of the technology are accompanied by details relating to the potential health and safety risks of the processes and products).

Relatedly, there are questions as to what effect attempts to further dissociate CDU from CCS would have upon people's opinions. Within countries less amenable to CCS, like Germany or the Netherlands (see Terwel, ter Mors & Daamen, 2012; van Os, Herber & Scholtens, 2014), one might hypothesise that perceptions of CDU would improve with greater dissociation from CCS. The same might not be said, however, for countries where CCS is considered less objectionable and/or seen to augment such processes (e.g. the UK).

In addition to investigating how alterations to the thematic framing of CDU affects opinions, there is the connected question about how the *extent* of the information provided to participants might affect their opinions of the technology. Given the time restrictions placed on the interviews, the information provided was limited in scope, which could be construed

as a limitation of this research. Indeed, while most interviewees agreed that their knowledge of CDU had increased through participation, they still recognised that there was much they did not know. As such, whether or not the opinions registered in our study would also arise if interviewees were provided with more comprehensive details about the technology remains an open question.

That being said, it has also been argued elsewhere (see Upham & Roberts, 2011; Upham et al., 2015) that if people in real-world settings form and express opinions about new technology based upon exposure to very limited information (e.g. short news articles), then the opinions derived from short focus-groups or questionnaires should not be too dissimilar to this. If so, then one could view the perceptions registered within our study to be akin in some regards to those that might be formed outside the interview context.

Beyond developing a deeper appreciation of the public attitudes towards CDU, another priority for future research should be to elucidate more about any perceptual divergences in perceptions and acceptance of CDU within different groups. While an obvious starting point for such investigations would be to explore and overlap or divergence in expert and lay perceptions of CDU—bearing in mind the relations that this can share with communicative and deployment issues—the research could move beyond this to investigate the role that factors, such as education and gender cultures (Barke & Jenkins-Smith, 1993; Lee, 2016). Furthermore, it was clear from the current research that the diffuse support for CDU was tied, at least to some extent, to the perceived lack of personal relevance of the technology. It remains an open question as to whether or not this diffuse support will be retained in scenarios where participants are more directly identified as the target of risk (e.g. recipients of a local facility) (Sjöberg, 2000).

5. Conclusion

The aim of this study was to provide fresh insight into emerging lay-public perceptions of CDU in two European countries (i.e. the UK and Germany). We sought to illuminate participants' opinions regarding the general concept, its techno-economic feasibility and the societal consequences that might result from investment in the technology.

The interviews revealed that while awareness of CDU was low, there was generally tentative support for the concept. The caveats that interviewees placed upon their support were manifold but appeared to primarily stem from a self-claimed lack of knowledge about the technology, as well as scepticism over the claimed environmental benefits of the technology. The focus on the environmental benefits of the technology appeared to relate to the framing of CDU as a 'green' technology option within the interviews.

Although the opinions of our UK and German interviewees were broadly similar, there were occasional differences. Systematic research is now required to confirm if the themes emergent in our research are registered in larger, more diverse samples and to establish more about the extent, nature and implications of any cross-national differences.

Finally, while we argue that the findings of this research hold potential for developing materials designed to foster wider public debate about CDU, this aim should not be conflated with the more simplistic objective of using information as a means of generating public support for the technology (see Sturgis & Allum, 2004). A growing literature argues against 'knowledge deficit' thinking as being the root cause of objections towards technologies (and other sources of social conflict) and also sometimes calls into question the promotion of scientific literacy as the solution to such problems (Nisbet & Scheufele, 2009).

Acknowledgments

The authors would like to thank Rebecca L. Radford for her assistance in preparing and conducting the UK interviews and Henriette Naims for advice and suggestions with the German interviews. This research is funded by the CO2Chem network (www.co2chem.co.uk) under EPSRC grants EP/H035702/1 and EP/K007947/1.

References

Apt, J., & Fischhoff, B. (2006). Power and People. *The Electricity Journal*, *19*(9), 17–25. http://doi.org/10.1016/j.tej.2006.09.008

Arning, K., Van Heek, J., & Ziefle, M. (2017). "Risk perception and acceptance of CDU consumer products in Germany." Paper presented at the 13th International Conference on Greenhouse Gas Control Technologies (GHGT-13), Lausanne, Switzerland, November 14-18, 2016.

Ashworth, P., Boughen, N., Mayhew, M., & Millar, F. (2010). From research to action: Now we have to move on CCS communication. *International Journal of Greenhouse Gas Control*, *4*(2), 426–433. http://doi.org/10.1016/j.ijggc.2009.10.012

Ashworth, P., Bradbury, J., Wade, S., Ynke Feenstra, C. F. J., Greenberg, S., Hund, G., & Mikunda, T. (2012). What's in store: Lessons from implementing CCS. *International Journal of Greenhouse Gas Control*, *9*, 402–409. http://doi.org/10.1016/j.ijggc.2012.04.012

Barke, R. & Jenkins-Smith, H. (1993). Politics and scientific expertise: scientists, risk perception, and nuclear waste policy, *Risk Analysis, 13*(4), 425-439. http://doi.org/ 10.1111/j.1539-6924.1993.tb00743.x

Beierle, T. C., & Cayford, J. (2002). *Democracy in practice: Public participation in environmental decisions.* Washington D.C.: Resources for the Future Press.

Boot-Handford, M. E., Abanades, J. C., Anthony, E. J., Blunt, M. J., Brandani, S., Mac Dowell, N., … Fennell, P. S. (2014). Carbon capture and storage update. *Energy & Environmental Science*, *7*(1), 130–189. http://doi.org/10.1039/C3EE42350F

Bradbury, J., Ray, I., Peterson, T., Wade, S., Wong-Parodi, G., & Feldpausch, A. (2009). The Role of Social Factors in Shaping Public Perceptions of CCS: Results of Multi-State Focus Group Interviews in the U.S. *Energy Procedia*, *1*(1), 4665–4672. http://doi.org/10.1016/j.egypro.2009.02.289

Brooks, J., Mccluskey, S., Turley, E., & King, N. (2015). The Utility of Template Analysis in Qualitative Psychology Research. *Qualitative Research in Psychology*, *12*(February 2015), 202–222. http://doi.org/10.1080/14780887.2014.955224

Bruhn, T., Naims, H., & Olfe-Kräutlein, B. (2016). Separating the debate on CO2 utilisation from carbon capture and storage. *Environmental Science & Policy*, *60*, 38–43. http://doi.org/10.1016/j.envsci.2016.03.001

Brunsting, S., Upham, P., Dütschke, E., De Best Waldhober, M., Oltra, C., Desbarats, J., … Reiner, D. (2011). Communicating CCS: Applying communications theory to public perceptions of carbon capture and storage. *International Journal of Greenhouse Gas Control*, *5*(6), 1651–1662. http://doi.org/10.1016/j.ijggc.2011.09.012

Chopyak, J. (2002). Public participation in science and technology decision making: trends for the future. *Technology in Society*, *24*(1-2), 155–166. http://doi.org/doi: 10.1016/s0160-791x(01)00051-3

Creighton, J. L. (2005). *The public participation handbook: making better decisions through citizen involvement.* John Wiley & Sons.

de Best-Waldhober, M., Daamen, D., & Faaij, A. (2009). Informed and uninformed public opinions on CO_2 capture and storage technologies in the Netherlands. *International Journal of Greenhouse Gas Control*, *3*(3), 322–332. http://doi.org/10.1016/j.ijggc.2008.09.001

de Vries, G., Terwel, B. W., & Ellemers, N. (2016). Perceptions of manipulation and judgments of illegitimacy: Pitfalls in the use of emphasis framing when communicating about CO_2 capture and storage. *Environmental Communication*, *10*(2), 206-226.

de Vries, G., Terwel, B. W., Ellemers, N., & Daamen, D. D. L. (2015). Sustainability or profitability? How communicated motives for environmental policy affect public perceptions of corporate greenwashing. *Corporate Social Responsibility and Environmental Management*, *22*(3), 142–154. http://doi.org/10.1002/csr.1327

Devine-Wright, P. (2011). Public engagement with large-scale renewable energy technologies: Breaking the cycle of NIMBYism. *Wiley Interdisciplinary Reviews: Climate Change*, *2*(1), 19–26. http://doi.org/10.1002/wcc.89

Druckman, J. N., & Bolsen, T. (2011). Framing, motivated reasoning, and opinions about emergent technologies. *Journal of Communication*, *61*(4), 659–688. http://doi.org/10.1111/j.1460-2466.2011.01562.x

Esser, J. (1998). Alive and Well after 25 Years: A Review of Groupthink Research. *Organizational Behavior and Human Decision Processes*, *73*, 116–41. http://doi.org/10.1006/obhd.1998.2758

Fraga, E., & Ng, M. (2015). FDCDU15 - Carbon Dioxide Utilisation: A framework for the analysis of the security of supply of utilising Carbon Dioxide as a chemical feedstock. *Faraday Discuss.*, *183*, 309–326. http://doi.org/10.1039/C5FD00038F

Frewer, L. J., Bergmann, K., Brennan, M., Lion, R., Meertens, R., Rowe, G., … Vereijken, C. (2011). Consumer response to novel agri-food technologies: Implications for predicting consumer acceptance of emerging food technologies. *Trends in Food Science and Technology*, *22*(8), 442–456. http://doi.org/10.1016/j.tifs.2011.05.005

Gibbins, J., & Chalmers, H. (2008). Carbon capture and storage. *Energy Policy*, *36*(12),

4317–4322. http://doi.org/10.1016/j.enpol.2008.09.058

Gupta, N., Fischer, A. R. H., & Frewer, L. J. (2012). Socio-psychological determinants of public acceptance of technologies: A review. *Public Understanding of Science (Bristol, England)*, *21*(7), 782–95. http://doi.org/10.1177/0963662510392485

Herrenbrück, R. (2015). *CCS in Deutschland*. RWTH Aarchen University. Retrieved from http://nbn-resolving.de/urn:nbn:de:0168-ssoar-456239

Hope, A. L. B., & Jones, C. R. (2014). The impact of religious faith on attitudes to environmental issues and Carbon Capture and Storage (CCS) technologies: A mixed methods study. *Technology in Society*, *38*, 48–59. http://doi.org/10.1016/j.techsoc.2014.02.003

Horlick-Jones, T., Walls, J., Rowe, G., Pidgeon, N., Poortinga, W., Murdock, G., & O'Riordan, T. (2007). *The GM debate: risk, politics and public engagement. Routledge.* Routledge.

Huijts, N. M. A., Molin, E. J. E., & Steg, L. (2012). Psychological factors influencing sustainable energy technology acceptance: A review-based comprehensive framework. *Renewable and Sustainable Energy Reviews*, *16*(1), 525–531. http://doi.org/10.1016/j.rser.2011.08.018

Johnsson, F., Reiner, D., Itaoka, K., & Herzog, H. (2010). Stakeholder attitudes on Carbon Capture and Storage—An international comparison. *International Journal of Greenhouse Gas Control*, *4*(2), 410–418. http://doi.org/10.1016/j.ijggc.2009.09.006

Jones, C. R., Eiser, J. R., & Gamble, T. R. (2012). Assessing the impact of framing on the comparative favourability of nuclear power as an electricity generating option in the UK. *Energy Policy*, *41*, 451–465. http://doi.org/10.1016/j.enpol.2011.11.006

Jones, C. R., & Jones, A. R. (2016). Two Blind Mice: It Is Time for Greater Collaboration between Engineers and Social Scientists around the RDD & D of Industrial Technologies. *C*, *2*(2), 16. http://doi.org/10.3390/c2020016

Jones, C. R., Kaklamanou, D., Stuttard, W. M., Radford, R. L., & Burley, J. (2015). Investigating public perceptions of carbon dioxide utilisation (CDU) technology: a mixed methods study. *Faraday Discuss.* http://doi.org/10.1039/C5FD00063G

Jones, C. R., Olfe-Kräutlein, B., Naims, H., & Armstrong, K. (2017). The social acceptance of carbon dioxide utilisation: A review and research agenda. *Frontiers in Energy Research*, *5*, 11. https://doi.org/10.3389/fenrg.2017.00011

Jones, C. R., Radford, R. L., Armstrong, K., & Styring, P. (2014). What a waste! Assessing public perceptions of Carbon Dioxide Utilisation technology. *Journal of CO2 Utilization*, *7*, 51–54. http://doi.org/10.1016/j.jcou.2014.05.001

Karakosta, C., Doukas, H., & Psarras, J. (2010). Technology transfer through climate change: Setting a sustainable energy pattern. *Renewable and Sustainable Energy Reviews*, *14*(6), 1546–1557. http://doi.org/10.1016/j.rser.2010.02.001

Kurath, M., & Gisler, P. (2009). Informing, involving or engaging? Science communication, in the ages of atom-, bio- and nanotechnology. *Public Understanding of Science*

(Bristol, England), *18*(5), 559–573. http://doi.org/10.1177/0963662509104723

L'Orange Seigo, S., Dohle, S., & Siegrist, M. (2014). Public perception of carbon capture and storage (CCS): A review. *Renewable and Sustainable Energy Reviews*, *38*, 848–863. http://doi.org/10.1016/j.rser.2014.07.017

Lee, R.P. (2016). Misconceptions and biases in German students' perception of multiple energy sources: implications for science education. *International Journal of Science Education, 38*(6), 1036 - 1056. http://dx.doi.org/10.1080/09500693.2016.1176277

Ladd, J. (2013). Stakeholder perceptions of socioenvironmental impact from unconventional natural gas development and hydraulic fracturing in Haynesville shale. *Journal of Rural Social Sciences*, *28*(2), 56–89.

Markewitz, P., Kuckshinrichs, W., Leitner, W., Linssen, J., Zapp, P., Bongartz, R., … Müller, T. E. (2012). Worldwide innovations in the development of carbon capture technologies and the utilization of CO2. *Energy & Environmental Science*, *5*(6), 7281. http://doi.org/10.1039/c2ee03403d

Mennicken, L., Janz, A., & Roth, S. (2016). The German R&D program for CO_2 utilization – innovations for a green economy. *Environmental Science and Pollution Research*, *23*(11), 11386-11392.

Miles, M. P., & Covin, J. G. (2000). Environmental marketing: A source of reputational competitive and financial advantage. *Journal of Business Ethics*, *23*, 299–311. http://doi.org/10.2307/25074246

Nisbet, M. C., & Scheufele, D. A. (2009). What's next for science communication? Promising directions and lingering distractions. *American Journal of Botany*, *96*(10), 1767-1778. http://doi.org/10.3732/ajb.0900041

Palanivelu, K. (2017). Climate change mitigation via utilization of carbon dioxide. In M. Goell & M. Sudhakar (eds.). *Carbon utilization: applications for the energy industry*. Singapore: Springer. http://doi.org/10.1007/978-981-10-3352-0_9

Perdan, S., Jones, C. R., & Azapagic, A. (2017). Public awareness and acceptance of carbon capture and utilisation in the UK. *Sustainable Production and Consumption*, *10*, 74-84. http://doi.org/10.1016/j.spc.2017.01.001

Peterson, T. R., Stephens, J. C., & Wilson, E. J. (2015). Public perception of and engagement with emerging low-carbon energy technologies: A literature review. *MRS Energy & Sustainability*, *2*, E11. http://doi.org/10.1557/mre.2015.12

Pidgeon, N. F., Corner, A. J., Parkhill, K., Spence, A. A., Butler, C., & Poortinga, W. (2012). Exploring early public responses to geoengineering. *Philosophical Transactions of The Royal Society A*, *370*, 4176–4196. http://doi.org/10.1098/rsta.2012.0099

Pietzner, K., Schumann, D., Tvedt, S. D., Torvatn, H. Y., Næss, R., Reiner, D. M., … Ziogou, F. (2011). Public awareness and perceptions of carbon dioxide capture and storage (CCS): Insights from surveys administered to representative samples in six European countries. *Energy Procedia*, *4*, 6300–6306. http://doi.org/10.1016/j.egypro.2011.02.645

Ricci, M., Bellaby, P., & Flynn, R. (2008). What do we know about public perceptions and acceptance of hydrogen? A critical review and new case study evidence. *International Journal of Hydrogen Energy*, *33*(21), 5868–5880. http://doi.org/10.1016/j.ijhydene.2008.07.106

SCOT (2017, April). CCU database. *Smart CO_2 Transformation.* Retrieved from: http://database.scotproject.org/

SETIS (2016, January). Carbon capture utilisation and storage. SETIS magazine, 11. Available at: https://setis.ec.europa.eu/system/files/setis-magazine_11_ccus_final.pdf

Shackley, S., Waterman, H., Godfroij, P., Reiner, D., Anderson, J., Draxlbauer, K., & Flach, T. (2007). Stakeholder perceptions of CO2 capture and storage in Europe: Results from a survey. *Energy Policy*, *35*(10), 5091–5108. http://doi.org/10.1016/j.enpol.2007.05.001

Sjöberg, L. (2000). Factors in risk perception. *Risk Analysis*, *20*(1), 1–11. http://doi.org/10.1111/0272-4332.00001

Sjöberg, L. (2015). Risk Perception: Experts and the Public. *European Psychologist*, *3*, 1–12. http://doi.org/10.1027/1016-9040.3.1.1.

Stirling, A. (2008). "Opening up" and "closing down": Power, participation, and pluralism in the social appraisal of technology, *33*(2), 262–294. http://doi.org/10.1177/0162243907311265

Sturgis, P., & Allum, N. (2004). Science in society: re-evaluating the deficit model of public attitudes. *Public understanding of science*, *13*(1), 55-74. https://doi.org/10.1177/0963662504042690

Styring, P., Quadrelli, E. A., & Armstrong, K. (2015). *Carbon Dioxide Utilisation: Closing the carbon cycle* (First edition). Amsterdam: Elsevier Ltd.

Terwel, B. W., Harinck, F., Ellemers, N., & Daamen, D. D. L. (2011). Going beyond the properties of CO_2 capture and storage (CCS) technology: How trust in stakeholders affects public acceptance of CCS. *International Journal of Greenhouse Gas Control*, *5*(2), 181–188. http://doi.org/10.1016/j.ijggc.2010.10.001

Terwel, B. W., ter Mors, E., & Daamen, D. D. L. (2012). It's not only about safety: Beliefs and attitudes of 811 local residents regarding a CCS project in Barendrecht. *International Journal of Greenhouse Gas Control*, *9*, 41–51. http://doi.org/10.1016/j.ijggc.2012.02.017

United Nations Framework Convention on Climate Change (UNFCCC) (2015). *Paris Agreement.* Available from: http://unfccc.int/files/essential_background/convention/application/pdf/english_paris_agreement.pdf

Upham, P., Oltra, C., & Boso, A. (2015). Towards a cross-paradigmatic framework of social acceptance of energy systems. *Energy Research and Social Science, 8*, 100-112. http://dx.doi.org/10.1016/j.erss.2015.05.003

Upham, P., & Roberts, T. (2011). Public perceptions of CCS: Emergent themes in pan-European focus groups and implications for communications. *International Journal of*

Greenhouse Gas Control, *5*(5), 1359–1367. http://doi.org/10.1016/j.ijggc.2011.06.005

van Heek, J., Arning, K., & Ziefle, M. (2017a). Reduce, reuse, recycle: Acceptance of CO_2-utilization for plastic products. *Energy Policy*, *105*, 53-66. http://doi.org/10.1016/j.enpol.2017.02.016

van Heek, J., Arning, K. & Ziefle, M. (2017b). "Differences between laypersons and experts in perceptions and acceptance of CO2-utilization for plastic products." Paper presented at the 13th International Conference on Greenhouse Gas Control Technologies (GHGT-13), Lausanne, Switzerland, November 14-18, 2016.

van Os, H. W. A., Herber, R., & Scholtens, B. (2014). Not under Our Back Yards? A case study of social acceptance of the Northern Netherlands CCS initiative. *Renewable and Sustainable Energy Reviews*, *30*, 923–942. http://doi.org/10.1016/j.rser.2013.11.037

Wallquist, L., Seigo, S. L. O., Visschers, V. H. M., & Siegrist, M. (2012). Public acceptance of CCS system elements: A conjoint measurement. *International Journal of Greenhouse Gas Control*, *6*, 77–83. http://doi.org/10.1016/j.ijggc.2011.11.008

Wallquist, L., Visschers, V. H. M., & Siegrist, M. (2009). Lay concepts on CCS deployment in Switzerland based on qualitative interviews. *International Journal of Greenhouse Gas Control*, *3*(5), 652–657. http://doi.org/10.1016/j.ijggc.2009.03.005

Wilsdon, J., & Willis, R. (2004). *See-through science: Why public engagement needs to move upstream.* Demos.

Wilson, G., Travaly, Y., Brun, T., Knippels, H., Armstrong, K., Styring, P., Krämer, D., Saussez, G., & Bolscher, H. (2015). A Vision for Smart CO_2 Transformation in Europe: Using CO 2 as a resource. SCOT project. Available at: http://www.scotproject.org/images/SCOT%20Vision.pdf

Wüstenhagen, R., Wolsink, M., & Bürer, M. J. (2007). Social acceptance of renewable energy innovation: An introduction to the concept. *Energy Policy*, *35*(5), 2683–2691. http://doi.org/10.1016/j.enpol.2006.12.001

APPENDIX A

Verbal introduction provided to participants before beginning interview questions (Note: Text was translated and read in German for the German interviews).

Carbon Dioxide (CO_2) emissions from human activities, like electricity generation at fossil fuel power stations, are believed to be contributing to global warming and climate change. Efforts to reduce CO_2 emissions from such activities are needed to combat this problem. One method of doing this is using a process called Carbon Capture and Storage (CCS). CCS, in basic terms, captures CO_2 where it is produced (e.g., in the gas emissions from fossil fuel power stations) where upon it can be transported and stored, deep underground in 'geological reservoirs' (e.g., empty gas and oil fields under the North Sea). Carbon Capture and Storage (CCS) could reduce CO_2 emissions being released into the atmosphere but it is (a) financially costly because it increases the amount of fuel needed to run the power station; and (b) it permanently disposes of a potentially useful source of carbon for manufacturing things.

- **What if some of the captured CO_2 could be used to create chemicals, plastics and other products; products that could then be sold to offset some of the costs of CCS?**

Carbon Dioxide Utilisation (CDU) technologies hold promise for making use of the CO_2 from industrial processes, like fossil-fuel electricity generation. CDU uses CO_2 as a source of carbon for making things like plastics, cement, transport fuel, and pharmaceuticals. By using CDU, it might be possible to ease our reliance as a society on freshly sourced oil, gas and coal in the manufacture of these products. Captured CO_2 can also be used to assist in the recovery of fresh oil from oil fields (a process called enhanced oil recovery or EOR).

- **CDU could thus simultaneously help to limit releases of CO_2 into the atmosphere from large emitters (like power stations) and provide a use for the captured CO_2.**

Like CCS, CDU technologies will require a lot of energy to make them work. It is recognised that this energy must come from renewable sources (like solar power or wind power) to ensure that CDU technologies do not increase our reliance on fossil-fuel power stations.

While CDU technology is well understood, at present we know much less about what the public think of the technology. This survey is designed to investigate more about what people think of CDU in general and will ask you to evaluate some of the CDU technology options.

[i] Due to time and budgetary constraints the interviewee sample sizes in each country were not matched. However, as the intent behind this exploratory qualitative study was not to statistically compare and contrast the opinions of demographically representative samples from each country, this discrepancy in sample size was not considered to significantly undermine the purpose of the study.

[ii] How much do you think you know about CDU (1 = Not a lot; 2 = A little; 3 = A fair amount; 4 = A lot).

[iii] These case studies were active at the times of the research.

[iv] The questionnaire used within this study was the same as that used by Jones et al. (2014). As such, it also contained additional questions relating to interviewee's awareness and knowledge of CCS, as well as their attitudes (*"Overall, what is your attitude to…?"* Very positive; Fairly positive; Neutral; Fairly negative; Very negative; DK) and attitude certainty (*"How certain or uncertain are you of your attitude to…?"* Very certain; Fairly Certain; Neutral; Fairly Uncertain; Very Uncertain; DK) regarding both CDU and CCS. The survey was also administered both pre- and post-interview offering the potential to assess changes in awareness and attitudes resulting from participation within the interview procedure. However, due to the relatively small (and therefore statistically underpowered) sample size and qualitative nature of the current study, the responses to these additional questions are not analysed further.

[v] In the Germany-based sample, trust in regulation was seen to quell some of the uncertainty relating to CDU. This is akin to findings of research into other technologies (e.g. *agri-food technologies*, Frewer et al., 2011).