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Reconfiguring European industry for net-zero: a qualitative review of hydrogen and carbon capture utilization and storage benefits and implementation challenges†

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Based on a rich corpus of original mixed-methods research, this paper explores the benefits, barriers, and justice impacts of industrial decarbonization *via* hydrogen and carbon capture utilization and storage (CCUS) *via* European industrial firms located in UK clusters. It asks: (1) what are the technology dynamics and drivers of both hydrogen and CCUS in a real-world deployment context, including the state of deployment plans? (2) what are the possible benefits of CCUS and hydrogen deployment? (3) What are the most significant barriers and challenges facing CCUS and hydrogen implementation? (4) Who stands to "win" the most from deployment, who stands to "lose," what possible inequitable community impacts could emerge, and what impact will deployment have on vulnerable groups? We offer answers to these four questions based on extensive semi-structured research interviews (N = 111) triangulated with site visits to industrial clusters (N = 52) as well as an extensive secondary review of the academic literature. We conclude with clear policy insights that are now prevalent across UK and European industrial clusters as well as emerging and context-specific recommendations concerning the adoption of hydrogen and CCUS to achieve net-zero industry globally.

Broader context

Industrial decarbonisation—the pursuit of industrial systems of manufacturing and energy use that become zero-emissions or even achieve negative emissions—is an alarmingly urgent but enduring societal challenge. We advance knowledge about net-zero industry using a robust original dataset with empirical lessons from the UK for other sectors and countries wishing to design future decarbonization scenarios, pathways and policies.

1. Introduction

Industrial decarbonisation—the pursuit of industries that become zero-emissions or even achieve negative emissions---is an alarmingly urgent but enduring societal challenge.[1–4] While most published decarbonisation scenarios are framed at the wider system level (*e.g.* national level), the necessary transformation of industrial processes and institutions for achieving net-zero emissions needs to be shaped by the characteristics and needs of the particular industries present in a particular location, together with a range of well understood local contextual factors encompassing both geographical and resource constraints. In short, the concept of industrial decarbonization must account for industrial clusters.[5,6]

At present there is a wealth of emergent research looking at the social acceptability of individual technology options (*e.g.* renewable energy,[7] hydrogen[8] and CCS[9]), on community responses to local siting proposals (*e.g.* longstanding risk perceptions work on radioactive waste siting,[10] not-in-my-backyard (NIMBY) attitudes for wind energy,[11] distrust over shale gas[12]), and on community perceptions of local environmental risks (*e.g.* risk geography work on perceptions of poor air quality,[13] environmental contamination[14] and environmental

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justice movements[15]). In this vein, formal and informal assessments of societal needs and responses to technical and environmental changes have been conducted across the European Union[16] to evaluate the ethical and policy implications of different models of technical democracy and citizenship.[17,18] However, there is limited research on the acceptability to decarbonize regional industrial systems within broader societal contexts.

This research aims to address this notable gap while underscoring its high importance of both local context (UK) and international perspectives. Based on original site visits ($N = 52$) and research interviews ($N = 111$) as well as a targeted literature review, this study examines the technological attributes and drivers, benefits, risks and challenges, and equity and justice impacts of net-zero industry implementation across England, Scotland, and Wales. The study includes a focus on lock-in mechanisms and reorientation strategies possible within industry, as well as emerging innovation journeys (such as hydrogen and CCUS) and the mechanisms for achieving net-zero industrial emissions, ranging from invention, experiments, market niches, to upscaling and diffusion.

2. Background: the necessity of industrial carbon capture and hydrogen *via* clusters

Our study focuses on two core technical options for industrial decarbonization: carbon capture and storage (including carbon capture utilization and storage, otherwise referred to as CCUS) and hydrogen using a novel cluster framework.

2.1 Carbon capture and hydrogen at industrial scale

Achievement of net-zero industry is a pressing challenge given the relative lack of low-carbon options available for "hard to decarbonise" sectors such as steelmaking, cement manufacturing, and chemical production. CCUS represents a promising and cross-cutting solution to this formidable problem.[19] Carbon capture and storage is defined as energy systems "*requiring return of CO_2 from combustion or process gases or ambient air to the geosphere for geological time periods (i.e., thousands of years)*," whereas carbon capture and utilization is defined as "*carbon (as CO or CO_2) captured from one process and reused for another, reducing emissions from the initial process and potentially, but not necessarily, being released to the atmosphere again at some point in its processing*".[20] Numerous emerging technologies are available with adequate capture capacities and biotic and abiotic forms of carbon storage, and these can be coupled with utilization processes, such as enhanced oil recovery and biochar.[19] Despite the diversity of these technological options, the bulk of the world's currently operational CCS facilities utilize concentrated flows of carbon dioxide, for instance, from syngas production or natural gas processing, and the majority of carbon utilization projects are for enhanced oil recovery within the oil and gas sector.[20]

As of 2023, there were 41 commercially operating CCUS facilities with an aggregate removal capacity of about 50 million tons of carbon dioxide.[21] However, there were 392 CCUS facilities in various stages of planning and development with an aggregate CO_2 capture capacity of 361 million tons. Reflecting this growing interest in CO_2 capture, International Energy Agency (IEA) and Nordic energy research have even claimed that CCUS "*represents the most important option among new technologies for reducing industrial CO_2 emissions after 2030*".[22] Mathur *et al.* also recently argue that "*given growing global emissions reduction targets, carbon capture, utilization, and storage (CCUS) will likely play a crucial role in the decarbonization of some industrial processes*".[23]

Hydrogen represents another promising solution to the problem of industrial emissions, given that it is an abundant and energy-dense fuel capable of not just meeting industrial energy requirements but also providing long-duration energy storage.[24] It can be coupled to intermittent sources of renewable energy, notably wind power and solar power, and also be used in lieu of natural gas for peaking, for industrial process needs, or even as a feedstock in the metal sector *via* direct reduction of iron ore.[25]

Similar to CCUS, hydrogen is seen as a fundamental pillar of industrial decarbonization. As the IEA concluded, "*Strong hydrogen demand growth and the adoption of cleaner technologies for its production enable hydrogen and hydrogen-based fuels to avoid up to 60 Gt CO_2 emissions in 2021–2050 in the Net zero Emissions Scenario, representing 6% of total cumulative emissions reductions*".[26]

2.2 Industrial clusters as a promising unit of analysis

Most industrial decarbonization work has focused on specific industries such as steel, cement and concrete and chemicals or particular technologies, such as hydrogen and CCUS (mentioned above), or technology platforms such as electrification or renewable energy. However, in practice, implementing net-zero plans often cuts across both industries and technologies and involves spatial and economically concentrated clusters. The use of cluster theory as a framing lens is suggested to understand how the "agglomeration" or localisation of industries in industrial districts can bring positive synergies (productivity, prosperity, efficiency, innovation, entrepreneurship, spillovers) alongside other risks (lock-in, pollution, exposure to shocks),[27] as these industries undergo sustainable transitions towards low-carbon futures.

Clusters are defined by interconnections of geographically concentrated companies and industries, which evolve and exhibit different forms in different places.[28] That is, clusters are not limited to firms in the same industry, but often form along a value chain leveraging compatible technologies and activities. As such, emphasis on these interconnections and interdependencies is crucial in defining clusters.[29] According to Porter, "the geographic scope of a cluster is determined by the distance within which informational, transactional, incentive, and other efficiencies occur".[28] Further, Sovacool *et al.* state that clusters can be categorized spatially, as well as by differing types of industrial connections (hub and spoke, satellite, state-sponsored), by integration into value chains (vertical and horizontal), by strategy (trade-driven or knowledge driven), and by maturity (emergent, established, mature, in decline).[27]

Historically, two major challenges to the analysis of clusters have been: (a) the lack of a systematic approach to defining the industries that should be included in each cluster, and (b) the absence of consistent empirical data on cluster composition across a large sample of regional economies.[30] To meet these challenges, a taxonomy for industrial clusters can be used to delineate among cluster inputs and outputs, such as energy consumption, energy mix, and greenhouse gas emissions. Such as taxonomy can, moreover, help design effective industrial decarbonization options.[31] The United Kingdom (UK) government has taken such an approach, considering clusters, rather than single industries, in technical and policy-making plans.

3. Methods: research questions, case study selection and research design

We relied on a mixed methods approach to better explore the real-world dynamics and challenges facing industrial use of hydrogen and CCUS.

3.1 Research questions

We began by crafting research questions grounded in four key dimensions of hydrogen and CCUS mentioned in the literature.

First, a huge and ever-growing base of recent literature emphasizes the salience of technical factors concerning both hydrogen and CCUS, including technical[32–34] and techno-economic potential[35–37] and innovation systems,[38,39] to name a few. To engage with and build upon this literature, we thus ask: what are the technology dynamics and drivers of both hydrogen and CCUS in a real-world deployment context, including the state of deployment plans?

Second, the recent literature emphasizes a diverse array of co-benefits to industrial decarbonization, including those that are technical,[40,41] economic,[42–44] political,[5,45] and sociocultural.[46,47] We thus ask: what are the possible benefits of hydrogen and CCUS deployment?

Third, the emergent literature discusses risks and implementation challenges in depth, including environmental consequences,[44,48] geopolitical risks,[49] commercial risks,[50] contingency plans[51] and uncertainties.[52] We thus ask: what are the most significant barriers and challenges facing hydrogen and CCUS implementation?

Fourth, and finally, a tranche of literature emphasizes the equity and justice issues with industrial decarbonization, including studies discussing distributive justice or procedural justice[53] as well as inequities[54] and just transitions.[55–57] We therefore ask: who stands to ''win'' the most from deployment, who stands to ''lose,'' what possible inequitable community

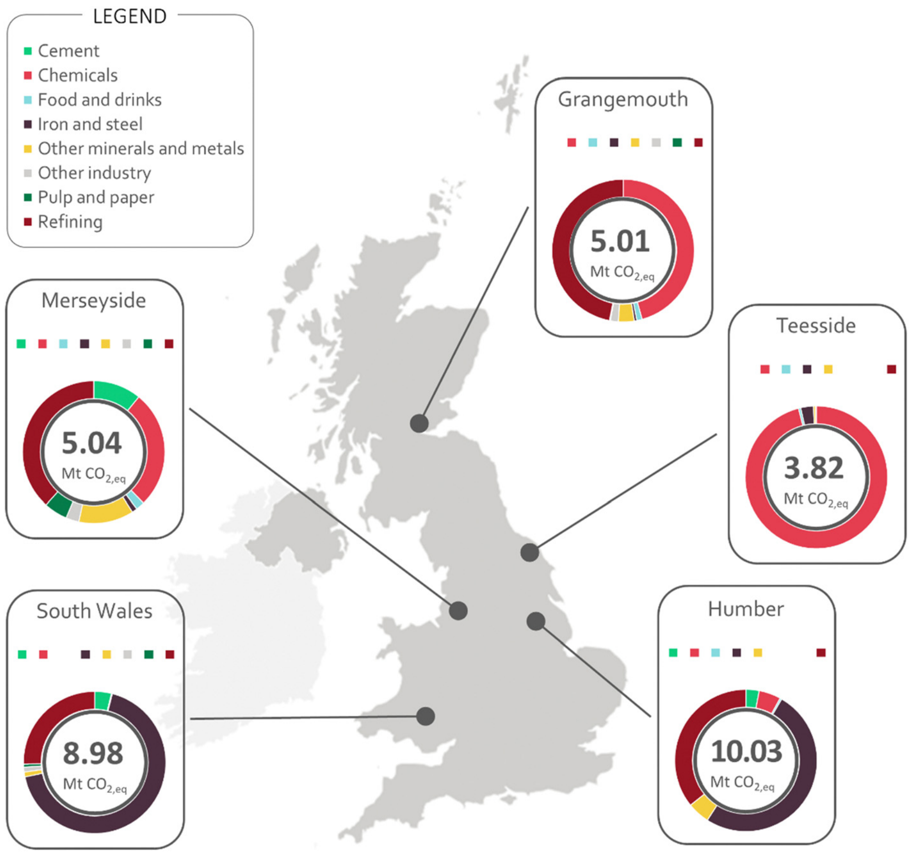

Fig. 1 Industrial emissions across five UK clusters. Share of emissions by industry type plotted in pie charts (see legend for each colour associated with an industry type). Data from ref. 58 (see Appendix Table 9).

Table 1 Main attributes of top 5 UK industrial clusters in terms of emissions

	Attributes								Anchor industries				
			Storage sites part of cluster		H_2 infrastructure								
Cluster name	Number of industrial sites considered	Number of local authority areas covered	CO_2	H_2	Industry	Exports	Transport	Buildings	Cement	Chemicals	Iron and steel	Other metals	Refining
Grangemouth	28[a]	14	✓		✓		✓	✓		●			●
Humber	26[a]/46[b]	4–10	✓	✓	✓		✓	✓	○		●	○	●
Merseyside	18[a]/54+[b]	5–16	✓	✓	✓	✓	✓	✓	○	●		○	●
South Wales	7[a]/44+[b]	5–12			✓		✓	✓			●		●
Teesside	5[a]/40[b]	5	✓		✓	✓	✓	✓		●			

Note: ●: industrial emissions over 1.0 Mt $CO_{2,eq}$; ○: industrial emissions over 0.5 Mt $CO_{2,eq}$. [a] Major sites only. [b] Including smaller sites. Source: authors.

impacts could emerge, and what impact will deployment have on vulnerable groups?

3.2 Case study selection of industrial clusters

This study applies our four questions in the context of industrial decarbonization in Europe, where many firms are piloting or implementing net-zero practices, particularly in the UK. The UK is taken as a qualitative case study of industrial decarbonization being pursued through distinct clusters, where plants from different European (and at times global) industries operate in close proximity. The five clusters with the highest emissions in the UK[58] are shown in Fig. 1 and form the basis of this assessment (Table 1). We catalogued the top five industrial clusters in terms of their total volume of carbon dioxide emissions based on government data,[58] and proceeded to conduct original research across all five sites of the Humber (10.03 Mt CO_2 per year), South Wales (8.98 Mt CO_2 per year), Merseyside (5.04 Mt CO_2 per year), Grangemouth (5.01 Mt CO_2 per year), and Teesside (3.82 Mt CO_2 per year) clusters. In each of these sites, cluster-specific decarbonisation roadmaps are being pursued with support from the UK Government. These roadmaps were published throughout 2023 (see Appendix Table 10).

3.3 Qualitative data collection

Data collection across these five clusters centred on semi-structured research interviews. Interviews were conducted with 111 expert respondents over the course of February 2022 to January 2023 (see Appendix Table 11). We intentionally sought to include a diverse range of perspectives from industry (who dominate our sample, given the topic) but also national government and policymakers, local authorities, and members of academia. Within industry, we were able to secure interviews with some of the most prominent actors in each cluster.

Our interview questions focused generally on technology implementation and experimentation; policy and governance;

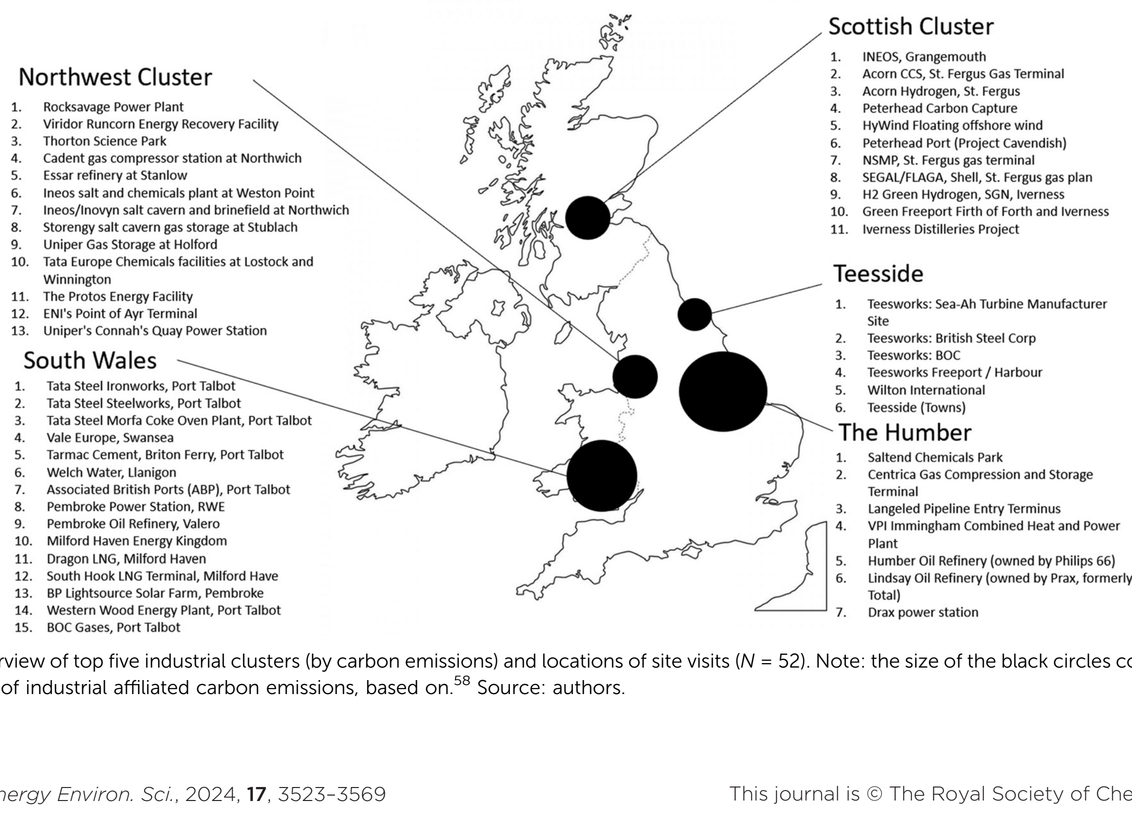

Fig. 2 Overview of top five industrial clusters (by carbon emissions) and locations of site visits (N = 52). Note: the size of the black circles corresponds to the volume of industrial affiliated carbon emissions, based on.[58] Source: authors.

benefits and risks; business strategy; and equity and vulnerability. Interviews lasted between 30 and 180 min, were recorded, and then fully transcribed. They were then coded by the authors inductively to identify recurring themes and topics. Our semi-structured interviews enabled the research team to gauge different topics that emerged in more flexibility and depth. To protect the anonymity of respondents, all specific qualitative data are referred to only by a generic respondent number. Ethics approval for the project was granted by the Social Sciences & Arts C-REC board at the University of Sussex with reference number ER/BS289/6.

To complement the interviews and match stated preferences with a type of revealed or observed preferences, the research team members also conducted a total of 52 site visits, shown in Fig. 2. These included seven visits to the Humber cluster, with accompanying visits to the cities and villages of Easington, Hull, Immingham, and Drax (in March 2022); 13 visits to the Northwest, Merseyside and HyNet cluster, accompanied by visits to the cities and villages of Liverpool, Manchester, Runcorn, Chester, Ellesmere Port, and Daresbury, as well as Flint in North Wales (in March 2022); 6 visits to the Teesside cluster, with accompanying visits of the cities of Redcar, Middlesborough, Billingham and High Clarence (in October 2022); 11 visits to the Grangemouth and Scottish Cluster, with accompanying visits of St. Fergus, Peterhead, Aberdeen, Inverness and Nairn (in January 2023); and 12 site visits to the South Wales Industrial Cluster, with accompanying visits to Port Talbot, Milford Haven, Swansea and Cardiff (in January 2023).

Finally, to triangulate the data from the interviews and site visits, our study is supplemented with an analysis of externally oriented presentations and reports, internal planning documents, trade-journals and other sector-specific publications. While these materials are not exhaustively cited in the references, they are implicitly leveraged to reinforce and support the detailed analysis of the interview and site visit data. This is the essence of the triangulation undertaken *via* the additional documentation.

To assess the content of the expert interviews, two approaches were adopted:

1. Qualitative assessment of expert interview content: the inductively coded interview transcripts were assessed in comparison to current publications from the literature. Retrieval of relevant literature was performed using both manual searches in three electronic databases (namely Web of Science, Scopus and Google Scholar) and a 'snowballing' approach[59] using a set of key references as a starting point (see Appendix Table 12);

2. Quantitative assessment of expert interview content: the inductive coding of expert interviews leads to the generation of 130 topical categories across five major groups (in Appendix Tables 13–17). The Jaccard distance metric is used to assess a measure of dissimilarity between the topical categories,[60] *via* the creation of a Jaccard coefficient/distance matrix. The Jaccard coefficient/distance matrix was generated by calculating the Jaccard distance/coefficients metrics for each pair of topical categories, that is, the ratio of the number of times one pair of topical categories is discussed in the expert interviews over the number of times at least one of the topical categories in the same pair is discussed. The resulting 130 × 130 matrix with triangular symmetry encodes all possible pair-wise values. This analysis is used to (a) rank the five most similar entries for each topical category (as the descending order of Jaccard coefficient values), and (b) identify the most dissimilar topics observed in the narratives among expert interviews (as the number of times a topical category reaches the maximum Jaccard distance value of 1 in comparison with other entries).

3.4 Limitations

Stated preference techniques, such as qualitative expert interviews, are commonly used in social science research like ours to elicit individuals' preferences, values, and intended behaviours. However, these techniques are susceptible to various biases that can affect the validity and reliability of the findings. Among the most important stated preference technique biases are:

• Social desirability bias: respondents may provide answers that they believe are socially acceptable or that align with the researcher's expectations, rather than their true preferences or behaviours.[61]

• Hypothetical bias: respondents may overstate their willingness to pay or engage in a behaviour when the situation is hypothetical, as compared to real-life decision-making.[62,63]

• Interviewer bias: the interviewer's characteristics, such as age, gender, or tone, may influence the respondents' answers, leading to biased results.[64]

• Question order bias: the order in which questions are presented can affect respondents' answers, as earlier questions may provide a context or frame of reference for later questions.[65]

• Selection bias: the sample of participants chosen for the study is not representative of the target population. This can lead to inaccurate generalizations and conclusions that do not reflect the reality or diversity in the field.[66]

• Participant or epistemic bias: participants respond in a way that is influenced by the study context and does not reflect their true preferences or behaviours. Epistemic bias is a related concept that refers to systematic deviations from rationality in people's stated beliefs and judgments.[67]

Moreover, and specific to our study, the sample of respondents was confined primarily to the UK and is further moderated by the authors' personal networks and contacts. We also avoided correction or problematization of the responses from our experts. Even if they were overconfident or, conversely, uninformed, we took them at face value.

We are aware of these biases and have taken steps to mitigate them in our work. To hedge these and related biases, we employed the following strategies for conducting our interviews, also in line with best practices in qualitative research design:[68–72]

• Indirect questioning without value assignment to particular types of responses, to reduce social desirability bias;

• Clear and detailed descriptions of the context for all questions, to minimize hypothetical bias;

• Interviews conducted with neutral tone as well as neutral question wording, to minimize interview bias;

Table 2 CCUS as an instrumental technology to achieve net zero and enable industrial decarbonization (n = 111)

Theme	Rank	Frequency by interview		Participant code	Representative quote
Facilitates society to reach net zero	1	63	56.75%	R1	*Companies very much want to find their way to net zero. How can they transition their economies or their sites and their sectors to this goal? This is what CCUS infrastructure is looking to fund, the infrastructure that would allow net zero to happen.*
Enables industry clusters	2	52	46.85%	R7	*So, the Teesside, for example, has individual projects, which might come together as a Teesside cluster. These clusters tend to be related to particular storage or let's call it, transport and storage networks because, without a transport and storage (T&S) network, it's impossible to get the CO_2 you capture to storage. So, there needs to be a T&S operator, and the clusters can come around a T&S operator. The same thing happens in the Northwest of England – you have HyNet and a T&S operator, and there will be a collection of emitters, so they form a cluster.*

Source: authors.

• As appropriate, randomized question ordering and free flowing discussion, to control for question order bias;

• Reliance on a critical stakeholder analysis in the selection of respondents which included those in favour of, as well as opposed to, industrial decarbonization as well as a sampling strategy seeking a range of diverse perspectives from industry, civil society, government, and academia, to minimize selection bias;

• Undertaking many interviews (N = 100+), coupled with the observation of revealed preferences *via* naturalistic observation to internally and externally triangulate the interview data to minimize participant and epistemic bias.

Consequently, despite the biases inherent in qualitative research designs, we set forth in our study to execute a robust, highly triangulated analysis.

4. Results: drivers, benefits, risks, and just transitions

Our interview data analysis focused on identifying the main benefits, risks, barriers, challenges and equity issues of deploying hydrogen and CCUS. Our results are organized based on economic, socio-cultural, political, geographic and environmental, and technical categories. Although we are breaking hydrogen and CCUS into distinct sections, the reader will note that in many cases, both approaches, rather than being competitive, are complementary or could even overlap. For this reason, in the Discussion we elaborate on how these technologies can operate simultaneously to get us closer towards net-zero industry.

4.1 The role of hydrogen and CCUS in industrial decarbonization and industrial clusters as enablers of these technologies

Based on their frequency counts, operational aspects of CCUS and hydrogen technologies for industrial decarbonization and emissions abatement feature as the most prominent subjects for exploration. Given that the UK government has openly outlined its substantial financial and policy support for CCUS, it is perhaps no surprise that 46.85% of our sample mentioned that CCUS is critical for enabling industry clusters, and 56.75% supported the idea that the use of CCUS is unavoidable to reach net zero. Participants commented, for instance, that CCUS represents a crucial alternative to repair the damage society has caused over "*250 years in total, but mostly over the most recent 50 to 70 years*". Table 2 captures the most representative quotes from our participants as well as their rank and frequency by interview.

In the case of hydrogen, results were similar, with 34.23% of our sample supporting the idea that hydrogen is essential for enabling industry clusters, and 55.85% shared the opinion that hydrogen deployment is inevitable to reach net zero. Experts commented that "*the government is interested in decarbonizing the Humber through things like hydrogen production*" or that "*industries can decarbonize the sites almost completely with hydrogen*". One participant even commented that if "*you're a heavy industry, and you need to decarbonize, you don't really have much alternative other than hydrogen*." Table 3 depicts the rankings and an illustrative quote representing hydrogen's prominent role in reaching net zero and as an enabler of industry clusters.

Perhaps unsurprisingly, participants from industries engaged with these technologies were more likely to support

Table 3 Hydrogen as an instrumental technology to achieve net zero and enable industrial decarbonization (n = 111). Source: authors

Theme	Rank	Frequency by interview		Participant code	Representative quote
Facilitates society to reach net zero	1	62	55.85%	R12	*This goes back to the 2008 climate change act, which says, "Thou shalt reduce thy emissions by 80% by 2050." Of course, we've now gone even further than that under Theresa May and gone for 100% emissions reduction effectively by 2050. Hydrogen could be a solution to reach that goal.*
Enables industry clusters	2	38	34.23%	R13	*All of a sudden, now, you are starting to see a jigsaw piece aligning. There's an industrial cluster based around the Humber. We have got lots of our methane coming into the Humber. The government is interested in decarbonizing the Humber through things like hydrogen production and industry clusters.*

Source: authors.

the argument that both approaches, CCUS and hydrogen, are fundamental to complying with climate targets. One expert commented in support of this argument: "*people from the industry are aware that the only way to comply with climate targets is through hydrogen and CCS; there is no other way to do it. Even the governments are fully aware of this; that's why they are pushing this agenda*". These views are further supported by some independent literature.[73,74] Although these technologies are at an early stage of commercial deployment, as competitiveness drives innovation in the years ahead[75] the technologies are expected to reach their full potential no later than 2060[76] or 2070.[77] The integration of these technologies is particularly relevant in "hard-to-abate" industries such as cement, chemicals, and steel.[78] Recent studies indicate that the most promising pathway for CCUS consists of first retrofitting current industrial plants and fossil fuel-based power stations and decreasing CO_2 cost for capture *via* near-term opportunities such as hydrogen production from steam methane reforming. Thereafter, it is argued, focus should be redirected to increasingly challenging applications, such as DAC. Bioenergy with CCS (BECCS) for carbon removal, an alternative to climate-neutral CO_2 for its use in multiple applications,[77] but most prominently in synthetic fuels,[79] is also expected to play a formidable role in the coming years.

Mitigating industrial emissions at the global level is vital since this sector alone emitted 9.0 Gt CO_2 in 2022, accounting for 25% of the global energy system's CO_2 emissions.[80] Industrial clusters account for about 20% of Europe's GHG emissions (excluding transportation). However, this percentage might increase to become the primary source of emissions as other sectors embark on earlier decarbonisation efforts.[81] Such a premise should take more relevance in light of the industrial sector's energy mix, which has remained largely unchanged and closely linked to fossil fuels, particularly coal.[82] Industry clusters, however, offer a solution to mitigating emissions, not only because of their proximity but also because of the size and aggregation of energy demand throughout industries that provide opportunities for electrification, systemic efficiencies, CCUS and an internal hydrogen market.[83] Experts commented on the benefits of industrial clusters and the integration of CCS and hydrogen in mitigating emissions. For instance, one expert elaborated on the complexity of post-combustion capture technologies on a distributed network and noted: "*If you have just got one major hydrogen production facility and one carbon capture facility and distribution facility, it is much easier to manage. Rather than having a whole suite of distributive propositions*." Another expert commented that although these technologies are "*currently expensive, they become economically feasible when are integrated as part of an industrial cluster, where multiple plants from different* industries *operate in close proximity*." Research on this topic supports our expert's view and argues in favour of the rationale for building clusters to facilitate mobilizing CO_2 from several plants, storage of the CO_2 in empty gas fields or saline aquifers and enabling "blue" hydrogen production at large scale from natural gas.[6]

4.2 Hydrogen sociotechnical benefits

We classified the sociotechnical benefits of hydrogen into the following categories: economic, sociocultural, political, geographic, and technical. The following sections discuss how these benefits emerged during the expert interviews.

4.2.1 The economic benefits of hydrogen deployment. The economic benefits of hydrogen vary from job creation and the possibility of expanding to multiple transport markets to retrofitting natural gas infrastructure and avoiding stranded assets during energy transition. For example, a participant commented on the benefits of deploying hydrogen from a holistic approach by noting that "*this isn't just about the industrial companies around HyNet. This is about investments, skills, jobs, economic growth and opportunities for the whole of the Northwest* [Merseyside cluster]." Research corroborates this participant's view, showing that in the UK, the hydrogen economy could deliver £4.4 billion in investments in developing hydrogen grids by 2035, over 8000 jobs are expected to be created through supply chain partners, and another 9000 jobs might be enabled through the network companies.[84] Within the next ten years, as investments increase to £6.8 billion, the UK could create over 25 000 highly skilled green jobs. The benefits of hydrogen deployment are not limited to the UK. Throughout Europe, the hydrogen economy could create about 900 000 jobs within a similar timeframe.[85]

Another expert noted that hydrogen could be "*used to power ships, vehicles and aviation as net zero fuel in the future is a huge market for hydrogen production.*" For example, research has highlighted the potential contributions of hydrogen in the transport sector,[24] with studies reporting that hydrogen enables substantial costs and emissions reductions for on-road transportation[86,87] (although we note that this application is widely debated), shipping[88,89] and aviation.[90,91] Appendix Table 18 illustrates experts' perceptions of how hydrogen could contribute to economic development in numerous ways.

4.2.2 The socio-cultural benefits of hydrogen deployment. Expressed socio-cultural benefits were also varied and ranged from promoting a culture of cooperation, knowledge exchange and innovation to providing cheaper energy services to consumers. Regarding cooperation, the Industrial Decarbonisation Research and Innovation Centre (IDRIC) in the UK, which has a strong focus on hydrogen, is a £30 million project that seeks to decarbonize industry through a collaborative multistakeholder approach that includes academics, industry and government.[92] The EU and Japan intensified their cooperation on hydrogen to spur innovation and to develop an international hydrogen market and upskilling and reskilling the workforce, as well as developing attractive policies, regulations, incentives and subsidies for hydrogen deployment.[93] The US Department of Energy,[94] through the Hydrogen and Fuel Cell Technologies Office, advances collaborative schemes among multiple stakeholders, including small businesses, to encourage hydrogen production, infrastructure, delivery, storage, and multiple hydrogen end uses across transportation and industrial applications. Showcasing this cooperation spirit, one expert expressed, "*one of the big things we talk about in the Humber and the East Coast Cluster is that if one of us wins, we all win*." Another participant suggested that there is a "*collective feeling of collaboration*" and a common goal to "*make this work.*"

Another benefit of deploying hydrogen in the UK's clusters is that it already has a trained workforce, as well as existing infrastructure. A participant indicated that "*we have been handling and moving hydrogen for 70 years. We have 1600 miles of dedicated hydrogen pipeline. We know how to handle it. We know how to move it. We know how to respond to an emergency. We know how to prevent emergencies. We know how to leak-detect*." At least in Europe, planning and understanding for hydrogen training and education began during the early 2000s through the European Technology Platform for Hydrogen and Fuel Cells (HFP).[95] This program sought to thoroughly map current and future training and education needs across schools, academia, government and industry sectors.[96]

Appendix Table 19 captures experts' perceptions of how further integrating hydrogen into energy systems could contribute to multiple socio-cultural benefits.

4.2.3 The political benefits of hydrogen deployment. The mentioned political benefits emerging from hydrogen mostly dealt with national aspects, from achieving energy security and independence to increasing national competitiveness and receiving public and private support. Regarding the first benefit, one participant indicated, "*hydrogen can help countries in becoming self-sufficient in terms of energy, making them more secure and independent against external shocks*." The UK government, indeed, perceives hydrogen as not only critical in mitigating emissions from industry,[97] but also fundamental for energy security.[98] Recent research also supports this perspective, suggesting that hydrogen can reduce dependency on fossil fuels sourced both domestically and internationally.[99,100] However, Al-Mufachi and Shah[101] underscore that due to the high costs of the energy transition, government support is expected to be necessary to reduce the financial burden on consumers. In our research, as shown below in Appendix Table 20, the most commonly mentioned political benefit is increasing national competitiveness. This suggests that successfully managing the transition to a hydrogen economy could lead to using resources more strategically, increasing the workforce technological capacity and capabilities and deployment and creation of a competitive advantage relative to other countries.[102,103]

4.2.4 The geographic and environmental benefits of hydrogen deployment. We did not expect to find that hydrogen's environmental and geographic benefits would be limited to three core themes, with the highest ranked, "geography of the project" featuring in only 26% of our sample responses. We suggest that this theme was the most salient because industrial clusters represent geographical concentrations of firms, and their proximity could facilitate industrial manufacturing and energy production.[6] Several researchers,[5] indeed, argued that adopting a place-based focus is vital to the success of industrial decarbonization. One participant commented that "*Industry clusters and facilitating hydrogen and CCUS deployment*" depends mostly on geography; "*connections are naturally available.*" Another benefit emerging from hydrogen adoption dealt with mitigating environmental issues beyond climate. On this topic, one participant noted that hydrogen not only serves as a technology to guarantee energy security and achieve climate targets but also to improve air quality, stating that "*the health risks from burning fuels are incredibly important; we should be talking more about air quality, but we only talk about climate change.*" Research on this matter has indicated that hydrogen could have distinct impacts on air quality depending on where and how fuel is generated and used.[104] For instance, combustion of hydrogen employed at industrial scales could represent a clean option from an air quality perspective.[105] Nevertheless, others point out that the direct combustion hydrogen can lead to NO_x emissions with negative environment impacts that are comparable to current fossil fuel combustion.[106] Appendix Table 21 notes rankings attributed to the environmental benefits of hydrogen use and deployment.

4.2.5 The technical benefits of hydrogen deployment. The technical benefits provided by hydrogen were not only the most numerous but also the most popular in terms of rankings. The first benefit was related to the potential to blend hydrogen with other gasses, particularly natural gas, or use hydrogen to create other energy vectors such as ammonia. Experts commented, "*We distribute and generate ammonia everywhere in the world today, and transport it, so why not use it as the carrier for hydrogen? In other words, you use ammonia for storage and then produce hydrogen as needed*". Indeed, a recent study by the National Renewable Energy Laboratory (NREL) suggests that blending hydrogen is a promising method to attain early market access for hydrogen while achieving near-term emissions reductions.[107] Blending hydrogen also touches on infrastructure since current natural gas pipelines are an encouraging strategy to incorporate hydrogen in the near-term.[108] The benefits from using existing infrastructure could deliver great economic benefits, according to one expert: "*you're talking something like 150 to 200 million pounds of saving by running a hydrogen line to Easington*."

Blending hydrogen for use in domestic heating has been a contentious issue in the UK. We note that during the period we conducted the expert interviews (February 2022 and January 2023), the UK government considered blending up to 20% hydrogen into the gas grid.[109] Even as of December 2022, the UK government actively contemplated requiring all residential gas boilers sold from 2026 to be equipped with the potential to burn hydrogen.[110] This series of events could have led our experts to support the idea of using hydrogen for industrial heating. Recent statements from the UK government, nevertheless, have now rejected this approach and note that there is "*no practical way*" that installing boilers of any type will "*deliver significant carbon savings and 'zero-carbon ready' homes*".[111] Previous evidence also contested the viability of using hydrogen for domestic heating and warned that there are too many technical challenges to overcome to make hydrogen an economic and practical low-carbon heating option, with Rosenow[112] noting that hydrogen is not only less efficient but also more expensive than district heating, solar thermal and heat pumps. Hence, the discourse on hydrogen for domestic heating we believe will, in due course, not sway a opinions on the viability of hydrogen for industrial heating uses.

Appendix Table 22 ranks the views on the most prominent technical benefits of using hydrogen, along with illustrative quotes from experts supporting such benefits. We note that in Appendix Table 14, TRL refers to technology readiness level, which is a scale that was initially developed in the 1970s by the United States National Aeronautics and Space Administration (NASA) and now used widely as a means of describing the progress of a technology from basic research conducted in a lab (TRL 1) to a fully commercial technology that has been scaled-up and validated in an operational environment (TRL 9). Full details on the TRL framework have been described by the U.S. Department of Energy.[113]

4.3 CCUS sociotechnical benefits

We classified the sociotechnical benefits of CCUS following the same criteria as in hydrogen. In the following sections, we discuss how these benefits emerged during the expert interviews.

4.3.1 The economic benefits of CCUS deployment. Like the economic benefits of hydrogen deployment, the CCUS benefits also touched on job creation and long-term operations. Experts commented that "*Jobs is a big one, both in terms of the direct jobs from actually building and running the projects but also allowing manufacturing industry to continue manufacturing in a low-carbon way*" and that "*similar to other industrial facilities, a CCUS plant can last for several decades*." The expected economic benefits of CCUS deployment are significant, with research indicating that the gross value added could be as high as £2–4 billion per year by 2030, with a cumulative total market value of £15–35 billion.[114] Should 15–25 CCS installations transpire in the UK, it is estimated that between 15 000–30 000 could be created by 2030 in the industry,[115] with a total of 1.5 million jobs expected in industrial clusters over the same period.[116]

For CCUS to be economically viable and deliver long terms value, the industry must allow the integration of small and medium enterprises in new business models and innovation. Research on this topic suggests that innovation is not only necessary to achieve deep emissions reductions from both cost and practical perspectives, but also to make the industry more competitive.[117–119] One participant even suggested that "*SMEs are essential, [they] employ lots of people and can engage in different areas such as transport networks and CO_2 storage. It's all those support companies that provide the services, the replacement parts and so on that make CCUS feasible and able to deliver in innovation. I think SMEs are absolutely key*." Appendix Table 23 illustrates experts' perceptions of how CCUS could contribute to economic development in numerous ways.

4.3.2 The socio-cultural benefits of CCUS deployment. The socio-cultural benefits of CCUS discussed were also varied and included cooperation and knowledge exchange, leveraging untapped innovation, having a trained workforce and enabling public participation. As we observed for hydrogen, the potential for cooperation also featured as critical for CCUS deployment. Experts commented that: "*there is a very strong spirit of collaboration and support across the clusters. As much learning as you can get*." This sense of cooperation and knowledge exchange is reflected in the UK's government action plan, where they seek to develop partnerships between government, academia and industry to move beyond supporting CCUS through innovation to developing CCUS infrastructure and securing the full benefits of this technology.[120] It is thought that collaboration will enable the integration of new technologies and new business models. As one expert stated: "*there are definitely opportunities for new technologies to disrupt things like the amine or the chilled ammonia capture processes. There are a lot of smaller start-ups and also big companies that have invested in new technologies that will deliver transformative reductions in the cost of carbon capture. Cooperation among these companies is vital to release new business models and achieve climate targets.*"

Benefits related to having a trained and skilled workforce were also notable, with over 10% of our sample participants agreeing that this was a key benefit to deploying CCUS successfully. One expert put it simply: "*I think there is enough expertise and experience out there. I think you also have oil and gas companies, the likes of BPs and Shells of this world, or Harbour Energies of this world, as we have in our area, who are very familiar with operating gas or gas liquid systems. They are very familiar with operating reservoirs and drilling or pumping gas, etc.*" In terms of public participation, although CCUS project development often follows public participation principles,[121] there are areas for potential improvement, including lack of transparency, fairness and capacity building.[9,122,123] One participant made an astute observation: "*Our projects involve the public and the communities. They are essential for the project to advance; however, I think there's more room to make this involvement even better*." Appendix Table 24 captures experts' perceptions of how further integrating CCUS into the energy systems could contribute to multiple socio-cultural benefits.

4.3.3 The political benefits of CCUS deployment. Comments on the political benefits emerging from CCUS also dealt with national aspects in terms of increasing competitiveness, political support, trust in the projects, and providing energy security and independence to a country. One expert encapsulated the first three benefits, stating that "*CCUS can boost national competitiveness by positioning the UK as a leader in climate mitigation and sustainable technologies. This could bring investments and deliver high-skilled jobs. I think there's an overall kind of support around this idea; there is confidence in industry and government that they will deliver*." Research corroborates our expert's perspective since a number of studies note that CCUS will have a critical role in sustainable transformations, not only by delivering a cost-effective solution for large-scale emissions reductions but also as a needed means to develop competitive industries.[78,124,125]

The capacity of CCUS to deliver energy security and independence was ranked last by our participants. This could be due to the continued connection of CCUS to fossil fuels, with the assumption that the former will not lead to energy security. Nevertheless, several experts did foresee CCUS as increasing energy security. One expert commented that "*CCS will allow us to see the energy independence and security for the UK*". Research exploring the benefits of carbon capture also underscores energy security, stability and independence as one of its key attributes.[126,127] In the UK, this technology is perceived not only essential to achieving the 2050 climate targets but also to achieving energy security, overall.[97] Even the UK Climate Change Committee has described CCUS as a "*necessity, not an option*" to attain these benefits.[128] Appendix Table 25 depicts the key political benefits emerging from CCUS deployment.

4.3.4 The geographic and environmental benefits of CCUS deployment. The most salient benefit emerging from this category, like hydrogen, relates to a project's geography and thus ability to deliver local benefits or fit into sense of place. One participant clearly presented what this benefit entailed: "*The competitive advantage in the UK is nothing to do with the technology side, because I think the UK does not have competitive advantage through mastery of technology. It has an advantage because it has places in the North Sea where you can stick carbon dioxide, and places where you can stick it underneath the sea rather than underneath the land, where, if you tried to have land-based carbon storage, I think you would have a lot of local opposition to it. You'd have in the same issues we see with resistance to fracking. The fact that it's done offshore, outside, is actually an advantage for the UK. Having the North Sea is a big advantage in that respect*." Literature underscores this consideration and notes that the delivery of a sustainable industrial decarbonization strategy is often influenced by the location of the project.[129,130] For instance, in the EU, the North Sea is at the centre of CCUS deployment, with two facilities already storing 1.7 Mt CO_2 per year and at least 11 other projects with a combined capacity of almost 30 Mt per year being developed in Europe. Nearly 70% of industry and power generation emissions are located within 100 km of a potential storage site and 50% within 50 km.[131]

Regarding the environmental benefits of CCUS, the IEA has indicated that CCUS is essential to delivering the 2015 Paris Agreement.[132] In the UK, CCUS is considered a critical technology to achieve national carbon budgets and decarbonization.[128,133,134] Globally, carbon removal through BECCS could reach around 50 Mt CO_2 per year by 2030,[135] while in the UK CCUS is expected to reduce between 20 to 70 Mt CO_2 annual negative emissions by 2050.[136] From an overall perspective, the CCUS family of techniques and technologies to capture, use, and/or store CO_2 is considered fundamental to achieving international climate targets.[137,138] One expert put it simply: "*we need carbon removal and storage technologies if we want to reach net zero. Renewables alone won't do it.*" Appendix Table 26 depicts rankings attributed to the environmental and geographical benefits of CCUS deployment.

4.3.5 The technical benefits of CCUS deployment. Comments on the technical benefits of CCUS were split into two main threads. One was related to having the skills or infrastructure in place, while the other dealt with enabling technological processes. Regarding the first, one participant encapsulated both benefits *via* this comment in reference to incumbent firms, mostly in the oil and gas sector: "*they've got all of this infrastructure, all of these pipes and tubes and basins. They've got all of these skills around engineering, and the logical thing for them to do, therefore, is to deploy the technology*". However, despite such support, these views could be contested since research notes that CCUS's role in mitigation scenarios does not provide a clear picture of pipeline infrastructure requirements, creating an uncertain understanding of the barrier that such requirements might pose.[82] With respect to the CCUS workforce, Swennenhuis and colleagues report that[139] the present workforce in the North Sea matches the skills from CCS. In other words, they argue that the employment sustained by the oil and gas industry could also grow the CCUS industry.

Moreover, our participants noted that the technical benefits emerging from CCUS include enabling adjacent new technologies to operate, such as blue hydrogen and DAC. In this regard, the IEA reports that blue hydrogen generated from natural gas coupled with CCS is considered a key low-emission hydrogen production pathway. Their analysis envisions that by 2070, around a quarter of global hydrogen production could be derived from this method.[140] A participant also underscored the dominance of blue hydrogen when stating: "*for the coming period, we would expect the majority of hydrogen to be blue [hydrogen], we need to reduce CO_2 emissions quickly and for the majority of industries this is fastest way to reduce their emissions*." In addition DAC might help to offset hard-to-abate future emissions[141] because it possesses the opportunity for the following characteristics to be developed: large-scale CO_2 removal potential, low direct land and water footprint, siting flexibility and carbon storage permanency and high measurement certainty.[142,143]

Several applications of CCUS are already widely deployed today, including chemical absorption of CO_2 from ammonia production and natural gas processing, CO_2 use in fertiliser (urea) production, and long-distance pipeline transport and injection of CO_2 for EOR. In recent years, a variety of other CCUS applications have been demonstrated, but remain in early adoption stages, such as chemical absorption from coal-fired power generation and blue hydrogen production, compression of CO_2 from bioethanol production and coal-to-chemicals plants, and CO_2 storage in saline aquifers. Several other applications, including DAC and CO_2 capture from cement and iron and steel making are still at the demonstration or prototype stage. In each of these potential new applications, a range of CO_2 capture technologies need to be tailored to the particular conditions of each individual process. Appendix Table 27 ranks the most prominent technical benefits of using CCUS, along with illustrative quotes from experts supporting such benefits.

4.4 Risks and implementation challenges of hydrogen

In this section, we classify the challenges of hydrogen implementation through a sociotechnical lens.

4.4.1 The economic challenges of hydrogen deployment. The economic challenges noted for hydrogen ranged from initial implementation costs to the lack of incentives to deploy this technology, to inadequate business models, as well as future uncertainties emerging from integrating hydrogen business models into current operations. The high cost for deployment ranked highest, with over 33% of our sample reporting it. Our qualitative data suggests that hydrogen production could be the biggest cost component of most hydrogen projects, with experts commenting that "[hydrogen] *costs are very important to factor*" and that "*it will be very expensive to develop a hydrogen economy*."

Deloitte, a consultancy, corroborates our empirical data and reports that production technology alone (*i.e.* electrolysis and SMR) could cost the UK between £3.5 billion and £11.4 billion to support hydrogen demand by 2050.[144] This is underscored by BEIS and other research highlighting that attaining economically competitive hydrogen production costs is a major challenge but key to its integration into the energy system.[145–148]

In the business model comments, experts commented, for instance, that the main challenge for hydrogen deployment deals with ''*delivering adequate business models*'', particularly ''*the interaction between transport and storage business models*'' is what adds complexity to the hydrogen economy. Research on this topic notes that, although hydrogen is ready to scale up, its market remains in the early stages, and the uncertain future evolution of markets and technologies deters pioneers from making final investment decisions.[74,149] Another study[150] suggests that, given hydrogen's uncertain future, effective governmental measures are essential to mitigate risks and enhance the financial viability of hydrogen deployment. One expert encapsulated each of these respective hurdles—the challenges regarding inadequate business models, the lack of a hydrogen market and future economic uncertainties—by stating: ''*one of the difficulties with hydrogen is knowing whether you've got the markets for it or not, because you've got to have someplace to take it, either for transport or for industry, or maybe in some places more small-scale commercial or residential networks, but at the moment it's a big risk. I don't think the business models are yet in place.*''

Researchers also acknowledge the policy bottlenecks for industrial decarbonization *via* hydrogen; Dolci and colleagues[151] indicate that there are only a few supporting policies for using hydrogen in industry, with the most relevant examples developed in France and the Netherlands. France has offered a carbon price through the (''Contribution Climat-Énergie''), which was established in 2017 at 30.5€ per t CO_2, and by 2030 aims to achieve a level of 100€ per t CO_2. importance of policy support is underscored by the expert comment: ''*where are the incentives for these projects? We're not going to build this for charity; we will only build it if there's money to be made*.'' Appendix Table 28 illustrates experts' perceptions and multiple statements regarding the economic challenges to hydrogen deployment.

4.4.2 The socio-cultural challenges of hydrogen deployment. Comments concerning the socio-cultural challenges of hydrogen implementation were also varied and grouped into two categories. The first relates to a certain sense of resistance, whether in terms of trust or social opposition and the second deals with insufficient staff and untrained workforce to manage the hydrogen economy. Experts reported that concerns regarding trust mostly dealt with the ''*credibility of blue hydrogen vs. green, is it really green?*''; and ''*the safety of CO_2 transport and storage*'' while others commented that political and environmental organizations, such as Friends of the Earth and the Green Party, have been particularly resistant towards the implementation hydrogen, with one expert questioning: ''*why would they trust oil and gas companies?*''. Bensten and colleagues[8] similarly highlight that unclear communications about new hydrogen technologies could lead to public distrust in companies and politicians. Other studies have furthermore accentuated the increasing lack of public trust in the oil and gas industries,[152–154] at times leading to fierce face local opposition.[12,155,156] Participants commented on the subject of local opposition that ''*people don't want a pipeline; people don't want to have a plant near their house. I think that is the biggest social issue*.'' While other participants also highlighted that although most of these communities have been exposed to living close to heavy industries before, information campaigns and past experiences regarding environmental injustices and regional economic decadence have led some community members to contest the benefits of hydrogen projects around industrial clusters.

A second category of comments relates to an insufficient and untrained workforce to operate hydrogen infrastructure.[157] Research notes that underlying shortcomings in the design, manufacture and maintenance of hydrogen production and transport and storage require new training skills in the UK workforce.[50] Regardless of the hydrogen production pathway, a surge in proficient technicians would be essential for the widescale implementation of heating homes with hydrogen, using fuel cells for vehicles or decarbonizing industry.[158,159] Walker *et al.*[160] even warned that the transition to household hydrogen appliances could potentially strain the UK's local labour resources. Experts supported what the literature already indicates and stated that: ''*training for hydrogen, training people to service boilers and stuff, it's safety training, because there is a lot of hydrogen ready equipment, but I do not know if we have enough experienced staff to actually transition towards a hydrogen economy*''. Appendix Table 29 captures our experts' statements about the socio-cultural challenges of hydrogen deployment.

4.4.3 The political challenges hydrogen deployment. We identified 12 political challenges for hydrogen deployment, which spanned from tensions among stakeholders and unclear and unstable political strategies, to lack of coherent regulations and geographic governance. The highest-ranked challenge dealt with tensions and competition among stakeholders, with one participant explaining that, in megaprojects, ''*there are also disagreements and tensions for any big projects*.'' Other experts commented on the lack of institutional coordination and policy investments, with one participant suggesting that ''*it's very easy for politicians to make significant statements about targets, it's another thing for Treasury and the responsible department, in this case BEIS, to back that up with suitable policy and legislation as well as the money. I think, understandably, there's a bit of a governmental disconnect at the moment*.'' Research has noted that barriers to megaprojects are not always under the company's control,[161,162] and other factors, such as *politics*, could highly influence megaprojects' development by exacerbating problems and even perpetuating traditional business models that mostly benefit fossil fuels companies and politicians.[4] The literature on megaprojects and politics suggests that these two elements are entangled due to their high visibility, the need for long-term political support and patronage, and the redistribution of economic, social, and political power. The same study notes that political support is of paramount importance for low-carbon industrial megaprojects like hydrogen or CCS.

In contrast to other megaprojects, these technologies might not inherently generate commercially relevant new products or services for end-users, underscoring the significance of political support.[163]

Other project-relevant themes related to delays in project delivery and project scale. Participants commented that the steel industry is getting impatient because "*hydrogen DRI is nowhere near ready yet*" and that projects "*have been delayed over the last few years, which creates delays in the businesses applying for them and the business models moving forward*." The scale of a project also has a fundamental role in the implementation of hydrogen, not only in terms of costs (*e.g.* "*no one knows what the final costs for decarbonization will be, these keep adding up*"), but also in terms of management: "*It's really hard to get a sense of what's actually real. The aspirations are massive, but we don't have any large-scale green hydrogen or blue hydrogen. We don't have any large-scale hydrogen production happening in the UK currently*." Research has shown that delivery delays are often common in construction megaprojects ranging from a few months to several years. Meanwhile, the overrun costs of megaprojects could amount to more than 45% of the initial budget.[164–167]

The last political challenge dealt with geographic and geopolitical tensions, not only for potential impacts on local UK authorities, but also with regard to how the Ukrainian-Russia war influenced the development of the UK's industrial strategy. On the first theme, one expert suggested: "*I think some of this is a UK problem. We don't have that kind of Invest in Scotland, Invest in Wales kind of approach that I think the devolved authorities have. We are much more split up within the UK, you know, and very much around your existing industrial geography in clusters and stuff. Yes, it certainly is a challenge for us*." Van de Graaf[44] and Eicke[168] stress the importance of further investigating the geopolitics of hydrogen, arguing that hydrogen can profoundly alter the global energy trade map, giving rise to a new category of energy-exporting nations and redefining geopolitical affiliations and partnerships among countries. Van de Graaf notes that by establishing international frameworks and injecting investments into expanding hydrogen value chains, we could mitigate the risks of carbon lock-in, market fragmentation, and intensified geo-economic rivalry.[44]

With respect to the conflict between Russia and Ukraine, experts noted that energy price increases could lead to significant "*delays in the project.*" Gas prices had at the time of the interviews conducted indeed increased "*eightfold since the war started and has pushed us to reconsider UK's energy resilience and its hydrogen and renewables strategies.*" Literature on the impacts of the Ukraine-Russia conflict report that this war marked a turning point in European energy policies. Renewable energy sources are rapidly proving to be more cost-effective, which will have direct consequences on fossil fuel reliance in the coming years.[169] The implications of these geopolitical tensions, however, are complex owing to the prominence of Russian gas as a transition fuel, functioning as a substitute for nuclear energy and coal.[170,171] The result is that largescale investment decisions are being delayed due to the high energy demand from energy-intensive industries. Appendix Table 30 captures the multiple statements showcasing the political challenges for hydrogen deployment.

4.4.4 The environmental challenges of hydrogen deployment. The noted environmental challenges to hydrogen deployment mostly dealt with continuing to enable oil and gas companies to burn fossil fuels through, for instance, prioritizing blue hydrogen over green or other more sustainable renewable sources. The second argument was related to the idea that hydrogen will still generate emissions. On the first dimension, an expert commented: "*the only useful hydrogen is green hydrogen, but only for certain applications, and those include long-distance transport, steel production, and ammonia production, and maybe for combined heat and power in remote microgrids, but not for home heating, not for passenger vehicles, not for stationary electricity storage. And yeah, blue hydrogen is a scam, the same as brown or black hydrogen*." Another expert commented on a similar line: "*blue hydrogen with CCS just perpetuates continued gas exploration with all the challenges associated with going into sensitive parts of the planet and keep digging to find that additional gas*."

Researchers warn that vehicle manufacturers and the oil and gas industry may attempt to steer hydrogen's benefits to their own gain. These efforts could skew the narratives surrounding the benefit of the hydrogen transition, exacerbated through corporate lobbying, which goes against the principles of procedural justice.[172,173] Another study[4] echoes that sentiment, cautioning against excessive influence from the gas industry and strategies that are heavily reliant on blue hydrogen. The study notes that resistance against blue hydrogen has grown stronger, especially in light of recent scientific findings implying that blue hydrogen might have a more adverse climate impact than coal.[174] This perspective has also garnered significant media attention, with numerous newspaper articles showcasing this concern, both at the local and national levels. Such observations are all the more apparent given that about 96% of hydrogen is currently produced from fossil fuels[175] Even the IEA contests the oil and gas industry's business models moving forward and plans for operations aligned with a low-carbon future.[176] For instance, they note[177] that although global hydrogen production increased at a rate of 3% from 2021 to 2022 to about 95 million tons, it remains derived from natural gas (62% of global production), coal (21% of global production), and byproducts from the refining and petrochemical industries (16% of global production). Low-carbon or clean hydrogen production accounted for less than 1% of all production (Fig. 3).

Other notable challenges emerged from the emissions generated during hydrogen deployment. One expert commented: "[with blue hydrogen] *there is too much methane slip. So that negates any benefits you have got because methane is such a strong greenhouse gas, and just the parasitic energy to make it is about 40% of the output, so it is not efficient to do it that way, and it is a leaky process*". Another expert corroborated such a view and added: "*blue hydrogen has a lot of CO_2 that it is produced with it so that's a Scope One emission. That's important to consider*." Our experts' statements are validated by further research, underscoring that only when hydrogen is produced from low-

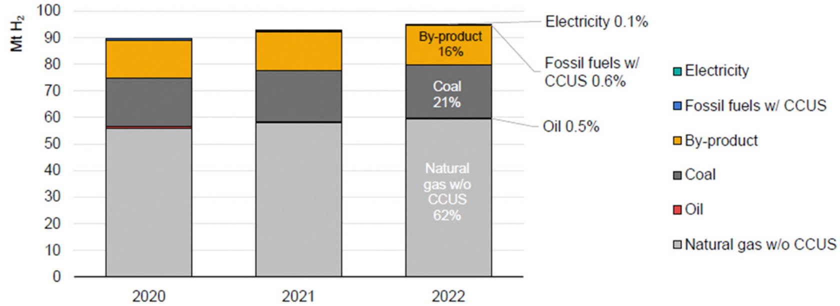

Fig. 3 Global hydrogen production by technology, 2020–2022. Source:[177] CCUS = carbon capture, utilisation and storage.

emissions sources, will residual CO_2 emissions be substantially removed.[178–181] Accounting for residual emissions is important because they are often not well-defined quantitatively and/or conceptually. Thus, stakeholders could struggle to communicate signals regarding the temporality of fossil fuel use.[182] Appendix Table 31 depicts the key environmental challenges identified by our experts.

4.4.5 The technical challenges of hydrogen deployment. The technical challenges to hydrogen deployment ranked highest and the most broad based among the responses we recorded. Hence, we note that technical issues currently represent the biggest perceived challenge to integrate hydrogen into the energy system. Some of the main challenges deal with what the literature has already identified in terms of leakage, transport and storage. For instance, Hauglustaine and colleagues[183] note that minimizing hydrogen leakage rates plays a central role in achieving a tangible climate advantage in the transition towards a hydrogen-based economy since leakage rates during transport, storage, production, and use could range from 1% to up to 20%.[184–186] Similarly, others argue that the potential contribution of hydrogen leakage to climate change could contest its overall benefits.[187,188] A more comprehensive understanding of hydrogen systems and the impacts of leakage could therefore aid in developing not only more appropriate hydrogen deployment targets but also more appropriate policies and regulations.

Other noted challenges concern developing the necessary infrastructure for hydrogen deployment. Current literature indicates that this is among the most prominent barriers that inhibit hydrogen expansion,[150,189,190] with Greene and colleagues[191] reporting that hydrogen infrastructure is becoming significantly more challenging to implement, when compared with the implementation requirements for electricity or renewables infrastructure. The more prominent issues related to infrastructure and the transportation of CO_2 from the generation plant to the storage site, the idea that needed technologies are still immature, and that they are not readily adaptable to current infrastructure. Similarly, there are uncertainties related to the conversion of infrastructure for production, delivery, and storage systems.[192–196] On this last point, one participant commented: "*you may have seen in the news, around 100% hydrogen in homes as well. That's interesting. It's a lot harder because you have to do the conversion of the equipment. Fundamentally, moving an entire village to hydrogen is quite a big undertaking.*" Other issues emerged from using the current natural gas infrastructure to deploy hydrogen. On this topic, hydrogen has different combustion properties from natural gas; therefore, changes in equipment are needed for use of hydrogen. Otherwise, one must expect a substantial loss of hydrogen's performance.[197] One expert commented: "*hydrogen has a much lower energy density on a volumetric basis, so you might need bigger pipework to get that hydrogen. You've already got a power station that was designed for natural gas, it wasn't designed for hydrogen, so maybe there's not enough space to fit all this bigger pipework.*"

Experts also contested technology readiness levels (TRLs) for hydrogen technologies, with most literature indicating that although some hydrogen technologies have gained maturity, others are still below the level required for commercial deployment.[24,198,199] Along this line, another study suggests that hydrogen's full maturity for industrial applications not be achieved until 2035.[200] Experts commented: "*In 40 years in the industry, I have never seen anything like this, like this adoption of our MPs and policymakers to promote an energy vector without the backing evidence.*" Finally, another theme that emerged during our data collection was related to hydrogen's energy inefficiency. One expert made an astute observation in this area and said: "*There's a bizarreness, because hydrogen is so inefficient to make means you need more energy. How does needing more energy sit with energy security?*." This statement comes from that the fact that converting power to hydrogen and then employing the hydrogen fuel to generate power has a low round-trip efficiency of 18–46%. Appendix Table 32 presents the 12 technical challenges identified by our experts, along with a statement supporting each of their views.

4.5 Risks and implementation challenges of CCUS

We have also classified the challenges of CCUS implementation through a sociotechnical lens, consistent with the prior section. In line with our hydrogen results, we note that experts also identified more risks to CCUS implementation compared to benefits. In the following sections, we elaborate on how the challenges of CCUS implementation discussed during the expert interviews.

4.5.1 The economic challenges of CCUS deployment. In some cases, the economic challenges discussed for CCUS mirrored those faced by hydrogen, including the high costs involved for its deployment, inadequate business models and uncertain profitability. Like in the hydrogen case, the biggest challenge to tackle is associated with the high costs of CCUS implementation, with over 36% of our sample indicating this as the biggest economic barrier. Research has also noted that, due to the elevated cost of CCUS and high investment risk, the technology has not yet fully entered commercialization[201,202] and this situation makes it challenging for companies to assume CCUS project investment returns.[42] Participants commented that CCUS' initial investment "*isjust unaffordable*" and that "*the costs are way, way, too high for us to consider. Also, the markets for carbon are not yet fully developed. We've looked at some initial business cases, we've never got as far as the FEED stage*". However, we note that although initial investments in CCUS are high, different applications have distinct costs. Costs can differ according to the concentration of CO_2 source, ranging from USD 15–25 per t CO_2 for industrial processes generating "pure" or highly concentrated CO_2 streams (such as natural gas processing or ethanol production) to USD 40–120 per t CO_2 for operations with "dilute" gas streams, such as power generation and cement production. Currently, the IEA indicates that DAC is the most expensive approach for carbon capture given the extremely dilute concentration of CO_2 in air.[118]

Experts also commented on the challenges intrinsic to developing CCUS business models. One expert suggested that "*establishing the business models to make these projects happen is the biggest challenge*" and that the energy sector and government need to develop a "*model that works with sufficient confidence for us to invest*" and that can "*guarantee certainty for the future*". Fan and colleagues[203] corroborate this statement by reporting the considerable uncertainties in CCUS' high investment costs, future returns, irreversible investments and a low carbon price that discourages the industry from getting involved. On the other hand, Nie *et al.*[204] note that carbon labelling subsidies are not contributing to cost reductions because of the elevated costs of CO_2-derived methanol production. Regarding subsidies, an expert expressed that "*subsidies are not going to fix the coordination failure between transport and storage and emitters who take on risk. Who owns those risks? We need more sophisticated strategies*." Appendix Table 33 illustrates experts' perceptions and multiple statements regarding the economic challenges to CCUS deployment.

4.5.2 The socio-cultural challenges of CCUS deployment. The noted socio-cultural challenges of CCUS implementation mirrored those from hydrogen; they were also configured into two broader categories: lack of trust and opposition to a project's development and second an untrained and insufficient workforce to operate the plants. In the first dimension, experts commented, for instance, that developers are concerned about the "*perception of the local population*" and that the "*biggest risk is social*", with people and, most precisely, "*local communities* [resisting] *change*", particularly, "*when it comes to building new infrastructure.*" Literature on public acceptance and opposition to carbon capture revolves around contesting the need for this technology within a rapidly-shifting landscape oriented toward eliminating technologies that support fossil fuel production[205] and a sceptical civil society questioning investments in CCS, particularly if using public funds could inadvertently support fossil fuel companies rather than contribute to emissions abatement or facilitating a just transition for a workforce engaged in carbon-intensive industries.[206] L'Orange Seigo *et al.*[9] captured similar sentiments regarding CCS. Their analysis of public perception studies conducted between 2002 and 2012 found that the ongoing reliance on fossil fuels for electricity production generates public concerns. Consequently, public perceptions of CCS largely centred around contesting the sustainability of this technology. In addition to local opposition, NIMBY sentiments are also a recurrent concern for CCS projects, which depicts a defence of communities' self-interests regarding property value and safety.[11,207,208] Other studies support this and indicate that technical experts and project developers often cite *the public* as a critical barrier to CCS, with local communities having more questions and concerns about CCS compared to more established technologies.[121]

An unskilled or non-existent CCUS workforce was also flagged as a key socio-cultural barrier. Experts commented that: "*particularly in the UK and particularly around these projects, the biggest risk, probably on our side, is the availability of skilled resources and a workforce to keep the projects going forward*." Another expert added to this complex dynamic concerning a particular industrial cluster in the UK: "*You are looking at somewhere between 25 000 to maybe 30 000 jobs to make this happen. But where are they going to come from? Where the Heck are they going to come from, right? Twenty-five thousand, it may be twenty thousand, maybe eighteen thousand, it may be twenty-one thousand, sort of who cares? It's a very large number, right? And we are going to need quite a lot of people, and we are going to need quite a lot of people in a relatively constrained space of time. That's just to decarbonise the Humber*." Budinis and colleagues[209] report that the availability of skilled labour in the CCS industry could become a potential constraint in the long term. Similarly, in their qualitative study, Gonzalez *et al.*[206] highlighted that the skills needed for CCS management is currently lacking. The IEA[210] also underscores such a dynamic and notes that a transformative change in the energy workforce is needed for widespread clean energy deployment, coupled with just transition policies to support workers affected by these shifts. Appendix Table 34 captures our experts' statements about the socio-cultural challenges of CCUS deployment.

4.5.3 The political challenges of CCUS deployment. We identified ten political challenges for CCUS deployment. Similar to the themes that emerged for hydrogen, these covered many areas, from unaligned tasks among stakeholders and a project's magnitude to a prevalent lack of cooperation and competition among stakeholders. In the political dimension, we noted that most issues emanated from the bureaucracy behind a project, unaligned tasks among stakeholders and an inconsistent policy strategy that perpetuates delays in deploying CCUS. One expert encapsulated such challenges when mentioning: "*There are no technical risks that we can envisage to prevent this from happening. In fact, we view ourselves as probably the lowest-risk option from an off-taker perspective. What can stand in the way is procrastination on support mechanisms,* *which don't allow us to trigger the investment in time. Another thing is the bureaucracy; sometimes it takes ages to keep a project moving. In other cases, the different partners involved in the project may not work well with others; in others, there are numerous changes in policy strategies. Megaprojects are always complex and take time to develop, but now we need to move forward urgently*." The political challenges to CCUS are very similar to those encountered for hydrogen; therefore, we will not elaborate extensively on this aspect. However, we note that, like in numerous energy megaprojects, such developments are key to political agendas and often become the focus of enormous political investments.[211] In addition, such projects are characterised by often conducting unsustainable practices that create land resiliency risks;[212] exhibit social, technical, economic, political, and psychological failures;[213] and these are often impeded by high levels of stakeholder conflict and technical complexity.[214–216]

Other discussed challenges entailed the geographic governance and the magnitude of projects. Experts expressed that technology is not really a problem since carbon capture is already an "*established technology*"; instead, they noted that "*the main problem is the scale of the project*" or that "*the scale is everything, that's our biggest challenge.*" The scale and the geographic scope of CCUS projects are interlinked, as the magnitude of these projects influences multiple local or regional jurisdictions. For instance, by 2030, the European Hydrogen Backbone anticipates that the hydrogen pipeline network across Europe will span approximately 28 000 km, impacting 28 jurisdictions in the continent.[217] Meanwhile, in continental Europe, numerous cross-border CCS infrastructure projects intended to access storage resources in the North Sea are being developed. The most recent (March 2023) includes a large open-access CO_2 transmission network to link Germany's industrial clusters to Belgium's Zeebrugge Port. The capacity of the pipeline is estimated to be 30 Mt CO_2 per year.[218] In addition to five cross-border CO_2 transportation networks operating now,[219] a European CO_2 pipeline network of up to 20 400 km by 2050 is also being considered.[220] Regarding carbon storage capacity, in the UK alone storage capacity is estimated at about 78 Gt CO_2 across more than 560 subsurface stores.[221] This shows that infrastructure will have different impacts on CCUS viability in different geographies; therefore, governance, accountability and costs could entail complications among stakeholders. One expert said: "*There are no standards in place to measure the emissions, especially when they are being transported across borders. Which is definitely going to be the case in Europe and also in the UK, transporting it to the North Sea. So, it is about coordinating across borders between the capturing facility and between the storing facility*." Appendix Table 35 depicts the key political challenges identified by our experts.

4.5.4 The environmental challenges of CCUS deployment. The noted environmental challenges to CCUS deployment mostly relate to perpetuating oil and gas companies to continue exploiting fossil fuels and the environmental externalities associated with CCUS technologies, such as transporting biomass for BECCS. Our experts commented on other issues that touch on the idea that even by implementing CCUS, emissions could still be released into the atmosphere. A final challenge touched on how CCUS could fail in help to meet climate targets. The challenge of allowing oil and gas companies to keep exploiting fossil fuels was most salient among our expert group, with almost a quarter of our sample commenting that this was the biggest issue in CCUS deployment. Participants commented, for example, that carbon capture only allows oil and gas companies "*to burn fuels and continue their carbon-intensive practices. Nothing is changing*." Another expert said CCS is "*enabling companies to sidestep the urgency to transition to renewables*." Research corroborates these views, noting for instance that CCS could not only perpetuate the *status quo* of fossil fuel use[222] but that if CCS takes longer to be deployed and more power plants are constructed, there is a higher risk of a further lock-in to unabated fossil fuels.[223] Further studies suggest that the fossil fuel industry supports CCS because the technology can prolong and increase profitability in the industry.[224] Stephens[225] reported more than a decade ago that the main economic advantage that CCS offered the fossil fuel industry is its ability to present a pathway towards a future with carbon constraints while still permitting the continued utilization of fossil fuels. In essence, Stephens argues that CCS can reshape how the fossil fuel industry perceives and plans for future challenges.

Additional studies have contested the inherent efficacy of CCUS due to the high concentrations of released CO_2 globally and its inability to address the wider implications on diverse ecosystems.[19] For instance, Zeaman[226] indicates that current DAC technologies require high energy demand due to the high pressure and temperature needed to regenerate the sorbent and subsequent release of CO_2. Should low-energy sources not tie in to DAC technologies, the benefits of DAC could be highly diminished. Fajardy and Mac Dowell raised a similar concern regarding BECCS.[227] They note that if biomass sourcing and transportation-related emissions are not addressed in the first place, the carbon benefits of this approach could be minimal.[227] Cuellar-Franca and Azapagic conclude that power plants with CCS have higher environmental impacts than those without since CCS involves unaccounted for coal mining and shipping emissions upstream and downstream of the CCS technology deployment.[228] The production of carbon capture solvent emissions during CO_2 absorption further contributes to CCS environmental impacts. Others have contested the efficiency of CCS by indicating that although carbon capture technologies aim to stop at least 90% of CO_2 emissions in most applications, as the technology evolves to reach nearly full efficiency (100%), costs will increase significantly, and it will demand more energy to capture more CO_2.[229] Dalla Longa and colleagues[230] corroborate this point and report that 35% of power generation from natural gas could go towards energizing industrial CCS facilities in the future. The environmental concerns of CCUS are even contested in the deployment of blue hydrogen, a primary emissions mitigation technology for the UK government. The potential issues with this approach are due to related emissions from its fossil fuel supply chain with methane leaks contributing significant greenhouse gas equivalent emissions.[231,232] Appendix Table 36 encapsulates statements from our respondents about the environmental challenges from CCUS.

4.5.5 The technical challenges of CCUS deployment. Compared to hydrogen, the technical challenges noted for CCUS deployment were less numerous and mostly dealt with infrastructural, geographic and technological issues and an unclear application of carbon utilisation. The issue of carbon leakage was the most prominent challenge raised by our interviewees. Participants commented that "*the impact of CO_2 leakage could be quite high, particularly locally*." Another participant comment that from personal experience storage could always leak, and rather than switching to renewables or green hydrogen, governments and industries supporting CCS "*are just storing future trouble*." Literature on the risks of CO_2 leakage indicates that the possibility that CO_2 stored underground could leak has led to contesting the benefits of CCUS as a climate mitigation strategy.[233] Particularly, potential leakages in fault seals, caprock and old wells' integrity have been considered major concerns.[234] Even though carbonate and sandstone reservoirs are usually regarded as the safest geological places due to their petrophysical properties,[235] Raza and colleagues[236] note that introducing CO_2 into storage sites, coupled with changing geomechanical factors, pressure, and temperature, could lead to geochemical interactions that create pathways for leakage during injection and storage. In fact, a commissioned UK study notes that any well drilled through the caprock's storage formation could potentially leak,[237] while another study corroborates that long-term CO_2 behaviour in the subsurface remains a key uncertainty for CCUS deployment.[238] A comprehensive list of CO_2 leakage patterns and causes is provided for the interested reader in further ref. 234 and 239–241.

Storage capacity surfaced as the second most prominent CCUS technical challenge, which, in a way, is closely linked to finding an adequate site for storage, our fifth-highest-ranked challenge. Zoback and Gorelick[242] report that about 27 Gt of CO_2 must be globally stored by 2050 yearly for this technology to have meaningful climate change mitigation impacts. Under these circumstances, the IEA notes that although global total

Fig. 4 The technology readiness level (TRL) of multiple technologies along the CCUS value chain. Source, retrieved from ref. 244.

capacity storage is between 8000 Gt and 55 000 Gt, meaning that we have sufficient storage capacity,[243] they also warn that not all storage capacity will be commercially accessible, and aspects such as public acceptance and land use constraints will ultimately determine where CO_2 storage sites can be exploited.[233] Experts on this theme suggested "*that's not necessarily about overall CO_2 storage volume; it is about how much CO_2 you can get into these reservoirs every year.*" Another expert questioned the UK's CCUS policy by stating that "*where will we put all the CO_2?.*" Transport infrastructure emerged as another prominent challenge. Developing this infrastructure represents tremendous capital costs[202] and only a few companies are developing transport and sequestration infrastructure for small-scale CO_2 transport applications related to DAC and BECCS.[79,227] On this topic an expert added "*CO_2 transport pipelines and geological storage are not only expensive but also require a lot of coordination, safety risks considerations and research. It is critical to have these aspects right.*"

Another challenge to CCUS arises from the fact that most of the technologies required for CCUS are not yet mature. This is shown in Fig. 4.

Finally, a last noted technical challenge dealt with the lack of clarity in carbon utilisation, with experts commenting that at least in the UK energy policy "*is all about carbon capture and storage. There is no usage in that at all*", another expert corroborated "*there is no clarity on the utilisation of carbon from a technical and business model perspective.*" Appendix Table 37 presents the seven technical challenges identified by our experts, along with an illustrative statement supporting each of their views.

4.6 Equity, vulnerability and just transitions

In this final part of the results section, we deal with equity, vulnerability and just transition. We who, from the transition to hydrogen and CCUS, will benefit the most? Our results suggest that big corporations and companies are likely to be the biggest winners, particularly companies from the oil and gas industry that have previous experience working in this area and that blue hydrogen and CCUS can perpetuate their traditional business models. Therefore, although CCUS and hydrogen are often depicted as mechanisms for job creation and retention, these technologies may fail to deliver a just transition since related costs and opportunities are not being fairly distributed across society.

4.6.1 Incumbency and consolidation of corporate power. We find that the equity and vulnerability impacts associated with hydrogen and CCUS are divided into two categories. The first related to how the benefits of hydrogen and CCUS deployment are likely to accrue to large firms. The second related to how local communities and energy consumers are, or might soon be, affected by the development of these technologies in megaprojects. Regarding the first dimension, experts commented, for instance, that "*blue hydrogen and many other business models emerging from CCS are a scam, designed to keep the fossil fuel industry in business. There's no other point of it*" and that CCUS and hydrogen will deliver "*hundreds of millions per year for Centrica [a company]. They are doing it because it's a profitable business foreseen in the future.*" Big corporations, particularly those belonging to the oil and gas industry, were also questioned regarding their lobbying strategies, with some experts commenting that they "*are experts at screwing money out of the public sector*" and taking advantage of regulations through their lobbying strategies. As one expert noted, "*they're really quite rapacious about it*". Another expert concluded that, particularly companies working on hydrogen "*have been very successful at lobbying*" compared to other companies that provide "*cleaner and perhaps cheaper energy alternatives*".

The literature suggests that investments in blue hydrogen and CCS will benefit oil and gas industries the most since extraction, storage, and infrastructure processes rely heavily on this industry's infrastructure.[74] A segment of studies[172,245] reveal that the agenda towards hydrogen and CCUS is predominantly dominated by oil and gas and car manufacturer corporations who, rather than supporting a net-zero-aligned transition, seek to entrench their existing interests and perpetuate their business models. Indeed, although big international oil and gas companies (*e.g.* Chevron and Exxon) have been very vocal regarding their awareness or potential willingness to transition to net-zero through promoting hydrogen and CCUS, research has contested their policies.[246,247] Both studies concurred that hydrocarbon operations would remain fundamental to the oil and gas business model as profits generated from renewable sources are currently lower than those of fossil fuels. Therefore, this industry has little incentive to change its financial and operational behaviours.

4.6.2 Exacerbation of local injustices. From the energy users and local communities' perspectives, experts were not sanguine about the equity and justice impacts of adopting hydrogen and CCUS. They warn that this transition could exacerbate fuel poverty and environmental and spatial injustices and increase inequality and unemployment in local communities. An experts commented, "*one of my fears, if we don't do anything, is we will start to lose industry* and *well-paid jobs*". Another participant added to this feeling of uncertainty when stating "*how do you know if you are going to sign contracts with companies that might disappear in one, two, or three years' time?.*"

4.6.3 Unfair impacts on vulnerable groups. Other sentiments towards CCUS and hydrogen deployment dealt with environmental injustices, with experts commenting that the geographies of related projects are already affecting low-income and other vulnerable groups. For instance, the advancement of projects will lead to "*industrial pipelines and the equipment that will have to go somewhere. So there will be a typical not in my backyard type of dynamics*". Another participant concurred and added that people living in the Humber and Teesside are the communities that have always "*been marginalised and are communities that don't earn much and don't produce much either, that's why they are building these projects there. This is a typical case of environmental injustice.*"

4.6.4 Negative workforce, skills, and employment concerns. Warnings about the erosion of a traditional workforce and an increase in unemployment were also prevalent issues brought by our participants. Experts' concerns revolved around the idea that big industries, such as iron and steel and cement and concrete, are battling to face the costs of decarbonisation and argued that such dynamics could "*cause these industries to drastically change, if not ultimately disappear, from the UK*", having tremendous economic and social impacts. One expert commented that if we see the iron and steel industry reducing emissions in the UK, it is not because the companies are adopting more efficient and cleaner technologies but rather "*in reality, we're seeing an industry die in front of our eyes.*" Sovacool underscores such social risks by considering how carbon storage and removal technologies could lead to local populations suffering from environmental harm,[248] arguing that, particularly in developing countries, a lack of stringent regulation could offset the climate benefits of carbon removal technologies.

Another related study explores the social dimensions and justice implications of emerging technologies, particularly carbon removal systems, and based on the evidence provided, questions whether such approaches lead to poverty reduction, job satisfaction, better working conditions, and a decrease in local conflicts over resource extractions.[249] The results from our research also add to the literature on environmental justice and NIMBY research, showing how environmental risks from mega-projects are unequally distributed by ethnicity and income in the UK. Finally, since our study also warns about unemployment and the unequal distribution of economic and material resources emerging from the deployment of hydrogen and CCUS, we have concern regarding these technologies' contributions towards a just transition. This concern is based on the observation that a significant portion of our sample indicated that, in their views, CCUS and hydrogen will likely fail on delivering fair and inclusive job opportunities. Appendix Table 38 ranks the most prominent equity and vulnerability challenges of CCUS and hydrogen deployment, along with illustrative quotes from experts.

5. Discussion: generalizable lessons to global deployment

We structure our analysis and discussion of the information collected around a two-pronged approach. First, we evaluate the key insights from the expert interviews in the context of different industrial cluster archetypes. The goal of this approach is to understand the thematic and narrative trends that emerge in the collective discourse of experts interviewed. Second, we leverage this evaluation to provide generalisable lessons to the global deployment of H_2 and CCUS towards industrial decarbonization.

5.1 Thematic and narrative trends on H_2 and CCUS for UK clusters

Analysis of the most common themes among expert interviews for the benefits and challenges of H_2 and CCUS deployment indicates a high degree of coherence between narrative trends, which reflects the potential complementarity of both technologies. As seen in Table 4, the most mentioned economic and socio-cultural themes, for both benefits and challenges, are aligned for H_2 and CCUS deployment.

For political and geographic and environmental themes, benefits are also aligned for H_2 and CCUS deployment. In the case of the most commonly mentioned political challenges, both technologies are seen as suffering from friction among stakeholders, albeit with different nuances. H_2 technology is seen as facing tensions from companies competing for funding and resources for deployment. CCUS technology, meanwhile,

Table 4 Comparison of most mentioned themes within our interviews (N = 111) for benefits and challenges of H_2 and CCUS deployment by category

Category	Benefits	Challenges
Economic	H_2 adoption can lead to benefits to the wider economy (*e.g.*, job creation and retainment) CCUS adoption can lead to benefits to the wider economy (*e.g.*, job creation and retainment)	H_2 deployment can result in high implementation costs CCUS deployment can result in high implementation costs
Socio-cultural	H_2 stimulates and supports cooperation and consensus among actors (industry, government, local authorities) CCUS stimulates and supports cooperation and consensus among actors (industry, government, local authorities)	H_2 projects may suffer from "spillover" lack of trust in the O&G industry from end consumers CCUS projects may suffer from "spillover" lack of trust in the O&G industry from end consumers
Political	H_2 can increase the competitiveness of industries both nationally and internationally CCUS can increase the competitiveness of industries both nationally and internationally	*H_2 projects may face tensions due to competition among companies for funding and resources* *CCUS stakeholders may be unaligned and communicating poorly*
Geographic and environmental	H_2 can leverage geographical proximity of industries and demand centres to expedite adoption CCUS can leverage geographical proximity of industries and demand centres to expedite adoption	*H_2 may not be "colour"-agnostic and result in predilection for certain technology options (e.g., blue H_2 over green H_2)* *CCUS may be opposed by society as it is seen as allowing the O&G industry to keep operating as usual*
Technical	H_2 can be produced via multiple technology value chains CCUS can reuse infrastructure that is already available	*H_2 adoption will require wide-scale infrastructure changes* *CCUS storage and transmission infrastructure must deal with leakage risks*

Note: italics indicate that most mentioned themes within a type differ between H_2 and CCUS. Source: authors.

faces lack of alignment of, and poor communication among, stakeholders. These perspectives reflect how each technology can permeate industrial clusters. Whether or not specific demand centres and/or existing production of grey H_2 is present or not in an industrial cluster can act as an anchoring point for H_2 deployment. For CCUS, CO_2 transmission and storage become more pronounced aspects of possible deployment. CO_2 volumes (both for transmission and storage) and distances (for transmission) can dictate whether a single industrial site or a collective of industries must coordinate efforts to enable a CCUS project, which may lead to the political challenge highlighted in the expert interviews.

On the geographic and environmental themes, the most mentioned challenge for CCUS deployment is whether social opposition may arise and prevent its use. This stakeholder challenge to CCUS may originate from perspectives that this technology allows O&G industries to continue to operate as usual, thus not addressing the underlying source of emissions. This thematic trend is also prominent in the themes and narratives related to equity and just transitions.

Focusing on the most prominent themes from stakeholders discussing each of the industrial clusters or the general landscape, alignment among narrative trends is also observed, as seen in Table 5. In all industrial clusters other than South Wales, the most commonly mentioned benefits for both H_2 and CCUS deployment are the fact that these technologies facilitate industries and the society reaching net zero goals. In terms of challenges, H_2 and CCUS implementation costs are the most mentioned theme among expert interviews discussing Merseyside and South Wales clusters. For expert interviews discussing the Humber cluster, the most mentioned H_2 and CCUS implementation challenges are related to investment delays resulting from future market uncertainties, with H_2 leakage risks in storage and transmission also being tied as the most mentioned H_2 challenge. The latter is also the case for the Teesside cluster, with CCUS implementation costs being also the most mentioned. The expert interviews discussing the Grangemouth cluster provide a different narrative trend, listing the potential risk of predilection for certain H_2 production technologies creating challenges to deployment, while and additional CCUS challenge is seen as end user distrust on the O&G industry affecting their perceptions of CCUS projects.

Focusing on the thematic and narrative trends concerning equity and justice, Table 6 provides an overview of main themes discussed by expert interviews for each cluster. Thematic and narrative trends are in line with those discussed in Section 4.6, and the most discussed themes are also consistently ranked within each cluster. For the more uniquely discussed themes, discussion on the Grangemouth and Humber clusters does not focus on the risk of potential "offshoring of emissions", while that theme is more pronounced in the South Wales cluster; this reflects the CO_2 geography of storage capacity accessible by each cluster, as presented in Section 2.1.

As evidenced in Sections 4.2.1 and 4.3.1, hydrogen and CCUS deployment is seen as a potential solution to create job opportunities for communities currently experiencing negative economic conditions, and which could face further hardship from an eventual closure of anchoring industrial sites. In such scenarios, industries are unable to economically comply with emissions regulations and must therefore instead shut down,

Table 5 Comparison of most mentioned themes within our interviews (N = 111) for benefits and challenges of H_2 and CCUS deployment by cluster stakeholder

Cluster/scope	Benefits	Challenges
Grangemouth	H_2 facilitates industries and society to reach net zero goals	*H_2 may not be "colour"-agnostic and result in predilection for certain technology options (e.g., blue H_2 over green H_2)*
	CCUS facilitates industries and society to reach net zero goals	*CCUS deployment can result in high implementation costs/CCUS projects may suffer from "spillover" lack of trust in the O&G industry from end consumers*
Humber	H_2 facilitates industries and society to reach net zero goals	H_2 investment may be delayed due to future market uncertainties/*H_2 storage and transmission infrastructure must deal with leakage risks (tied)*
	CCUS is an enabler of industry clusters/CCUS facilitates industries and society to reach net zero goals (tied)	CCUS investment may be delayed due to future market uncertainties
Merseyside	H_2 facilitates industries and society to reach net zero goals	H_2 deployment can result in high implementation costs
	CCUS facilitates industries and society to reach net zero goals	CCUS deployment can result in high implementation costs
South Wales	H_2 can be produced via multiple technology value chains	H_2 deployment can result in high implementation costs
	CCUS facilitates industries and society to reach net zero goals	CCUS deployment can result in high implementation costs
Teesside	H_2 facilitates industries and society to reach net zero goals	*H_2 storage and transmission infrastructure must deal with leakage risks*
	CCUS is an enabler of industry clusters/CCUS facilitates industries and society to reach net zero goals (tied)	*CCUS deployment can result in high implementation costs*
General	H_2 facilitates industries and society to reach net zero goals	*H_2 deployment can result in high implementation costs*
	CCUS facilitates industries and society to reach net zero goals	*CCUS storage and transmission infrastructure must deal with leakage risks*

Note: italics indicate that most mentioned themes within a cluster differ between H_2 and CCUS.

Table 6 Detailed thematic and narrative trends from our interviews (N = 111) concerning justice and equity considerations of industrial decarbonization

Themes	Cluster					General
	G	H	M	SW	T	
H_2 and CCUS adoption will result in higher energy costs for end consumers	●●●	●●[a]	●●●[a]	●●●[a]	●●[a]	●●●[a]
H_2 and CCUS may largely favour big companies and corporations capable of sizable investments	●●●[a]	●●	●●	●●●	●●	●●●
H_2 and CCUS adoption may erode demand for traditional workforce and eliminate jobs	●●●	●●	●●	●●	●●	●●●
H_2 and CCUS infrastructure costs will be partially borne by end users	●●●	●●	●●	●●	●●	●●
H_2 and CCUS projects may lead to outsourcing of jobs due to required highly skilled personnel available elsewhere	●●	●●	●●	●●	●	●●
H_2 and CCUS development may be influenced by lobbying efforts from O&G industry	●●●	●●	●	●●	●	●●
H_2 and CCUS projects may promote environmental injustices	●●	●	●	●●	●	●●
H_2 and CCUS are seen as ''greenwashing'' technologies to support O&G industry towards ''business-as-usual''	●●	●	●	●●	●	●
H_2 and CCUS additional costs may disproportionally impact low-income end consumers	●●	●●	●●	●●	●●	●●
H_2 and CCUS projects may not address unemployment affecting local communities due to mismatch in job skills	●●	●	●	●●	●	●●
H_2 and CCUS are not supported by heavy industries to the same extent that profit-generating activities are	●	●	●	●	●	●●
H_2 and CCUS adoption to replace natural gas will burden end users with costs associated with equipment changes	●●	●●	●	●●	●	●●
H_2 and CCUS projects can distort local job markets and exacerbate income inequality in local communities	●●	●	●	●●		●
H_2 and CCUS adoption may be distorted by state protectionism towards O&G industry	●		●	●	●	●
H_2 and CCUS may result in ''offshoring'' of emissions to developing and underdeveloped nations			●	●●	●	●
H_2 and CCUS may not address lack of diversity in the workforce			●			

Note: G: Grangemouth; H: Humber; M: Merseyside; SW: South Wales; T: Teesside; ●: mentioned less than 12.5%; ●●: mentioned less than 33.3%; ●●●: mentioned more than 33.3%. [a] Highest mentioned theme in cluster.

with negative outcomes cascading into the communities surrounding these industries. Thus, H_2 and CCUS adoption fulfills the dual purpose of enabling current industries to continue to operate (*i.e.*, job retainment), and to create new job opportunities (*i.e.*, new jobs creation). Industrial clusters socially ingrained industrial activities, such as at Teesside, Grangemouth and South Wales, are discussed as examples where community reinvigoration is possible. The potential negative aspects of H_2 and CCUS adoption on workforce dynamics, however, is not homogeneously discussed in these clusters. Distortion of local job markets and propagation of income inequality from an eventual deployment of H_2 and CCUS technologies is not a focus point in the discussion of the Teesside cluster, which is more compact and anchored by fewer heavy industry sites, while a more pressing theme in the other clusters, in particular the more sprawling clusters of Grangemouth and South Wales.

State protectionism towards the O&G cluster is tentatively discussed in all clusters other than the Humber, while discussion of whether H_2 and CCUS deployment can address the lack of diversity among workforce is yet to become a commonly discussed theme.

5.2 Generalisable lessons for global deployment of H_2 and CCUS

Finally, we outline the most discussed themes by expert interviews concerning the industrial clusters, and detail how these can provide a blueprint for generalisable lessons to the global deployment of H_2 and CCUS technologies. After ranking all of the themes captured by the interviews in terms of mention frequency, we use a similarity/dissimilarity index to aggregate themes along common narratives. Using the Jaccard coefficient/distance similarity matrix (Appendix Tables 13–17), it is possible to assess which themes are more commonly discussed in a pair-wise manner. The higher the Jaccard coefficient (J_c) value obtained, the more commonly discussed two themes are across all interviews, while a high Jaccard distance (J_d) value (which is the unit complement of J_c) represents the opposite. As such, the more often a theme scores a J_d value of 1, the more isolated it is from the other themes, and, thus, less common in the main narrative trends.

Using the five highest values of J_c for each theme, it is possible to assess which themes are not only more common (from the mention frequency), but also more commonly discussed together according to the expert interviews (Table 7). Fig. 5 provides a visualization of how these themes interconnect. The top 13 themes from all topical categories from the coding of expert interviews ranked in descending order from the highest to lowest number of total mentions across all interviews. The length of the bands on the circumference of the circle represents the sum of J_c scores for the top 5 topics for each entry and are color-coded according to five major groups (one for each of Sections 4.2–4.6), in addition to the ''other'' group. The summed scores for each band have all been normalized to 100% but the lengths nonetheless vary according to J_c score sum. Ribbons cutting across the circle represent the pairing between themes in topical categories, where the ribbon thickness represents the J_c score between two of the themes commonly discussed together. As seen in the 13th ranked theme, the highest J_c does not connect with the themes most commonly discussed together and hence provides a clear cutoff point between the clustering of the most mentioned themes (ranked 1–12) and the rest of the themes in all topical categories.

Based on the results shown in Table 8 and Fig. 5, a common theme among those interviewed were an orientation towards

Table 7 Top 12 themes most mentioned and discussed within our interview data (N = 111 respondents) on industrial decarbonization together

Rank	Theme
1	CCUS facilitates industries and society to reach net zero goals
2	H_2 facilitates industry clusters and society to reach net zero goals
3	CCUS is an enabler of industry clusters
4	H_2 may not be ''colour''-agnostic and result in predilection for certain technology options (*e.g.*, blue H_2 over green H_2)
5	H_2 can be produced *via* multiple technology value chains
6	CCUS adoption can lead to benefits to the wider economy (*e.g.*, job creation and retainment)
7	H_2 adoption can lead to benefits to the wider economy (*e.g.*, job creation and retainment)
8	CCUS stimulates and supports cooperation and consensus among actors (industry, government, local authorities)
9	CCUS deployment can result in high implementation costs
10	H_2 and CCUS adoption will result in higher energy costs for end consumers
11	CCUS storage and transmission infrastructure must deal with leakage risks
12	H_2 is an enabler of industry clusters

more positive than negative sentiments. Specifically, CCS is viewed as an enabler of industry clusters, providing the means for various sectors to significantly reduce their carbon footprint, thereby helping to achieve net zero goals. It has an additional role of fostering cooperation and consensus among a diverse set of actors from industry and government. However, with its deployment comes challenges, mainly high implementation costs and concerns regarding leakage risks associated with storage and transmission infrastructure. Hydrogen also has emerged as a catalyst for net zero. However, it is often noted that hydrogen can be produced by various means and inclination towards ''blue'' hydrogen over ''green'' is not unexpected for clusters with fossil fuel legacies and support for CCUS. This, however, hinges on the fact that hydrogen can be produced *via* various technology value chains, each with its own advantages and drawbacks. Both CCUS and hydrogen not only contribute to decarbonization but can have benefits to the broader economy. Their adoption can pave the way for job creation and retention, providing a socioeconomic boost to regions that host these industrial clusters. However, incurred energy costs for the end consumer should be considered as well.

Despite this general narrative, less commonly discussed, yet nonetheless important, sociotechnical themes were also observed from the data. The J_d metric provides insights into the more uniquely discussed themes that are presented in Table 8. These themes collectively provide an understanding of how moving H_2 and CCUS adoption to scale *via* clusters triggers concerns ranging from workforce development (Appendix Tables 29 and 34) and diversity (Table 4) to inclusion of small and medium businesses in emerging value chains (Appendix Table 23) to the technical challenges of material degradation from transporting hydrogen in pipelines (Appendix Table 32) and the ability to store carbon dioxide in a leak-proof, nearly permanent manner (Table 4). This diversity of themes reinforces one of our central messages, which is that policy makers must take a holistic view of H_2 and CCUS adoption that accounts for multiple interconnected social, political, economic and technological factors. Table 8 provides a list of the least discussed themes with main narrative trends.

6. Conclusion

Industrial decarbonization is perhaps the most challenging aspect of achieving global net-zero greenhouse gas emission ambitions. However, low-carbon H_2 and CCUS are emerging technology pathways that can make net-zero industry a reality. This study identified the key sociotechnical barriers, and potential catalysts, for the rapid adoption of these technologies (Section 4). Underpinning rapid adoption is deployment of H_2 and CCUS within industrial clusters, which bring together significant, if not complete, industrial value chains into a common geography to coordinate the demonstration and scale-up of novel technologies such as those explored in this paper.

The UK industrial clusters studied have diverse contexts (Section 2) and hence a key consideration of this work was to identify common aspects of low-carbon H_2 and CCUS production and use. That is, the technology dynamics and drivers (Section 4.1), potential benefits (Sections 4.2 and 4.3), barriers and challenges (Sections 4.4 and 4.5), and equity and just transitions considerations (Section 4.6) that are common to all clusters. Based on our findings, the predominant narrative is that H_2 and CCUS adoption are high cost in the near term but have substantial long-term and economy-wide benefits over the long run (Table 4). Implementation of these technologies, particularly CCUS, is moreover expected to face some degree of socio-cultural backlash related to concerns about the perpetuation of the oil and gas sector in the face of growing climate concerns, although the opportunity for deployment of these technologies to stimulate cooperation among diverse value-chain stakeholders is apparent. Importantly, H_2 and CCUS provide an opportunity for current infrastructure in industrial clusters to be used as the nucleus for evolution of a new technology paradigm that can increase regional and national competitiveness while making net zero industry viable.

Importantly, themes and narratives also emerged from the unique contexts of industrial clusters. For instance, the impact of H_2 and CCUS technologies on justice and equity considerations concerning local labour markets and workforce dynamics were particularly salient at Grangemouth, a somewhat dispersed cluster with multiple local authorities involved in planning and with refining serving as an anchor industry. Such considerations were much less salient at Teesside, a more dispersed cluster with fewer local authorities involved and just a single anchor industry (chemicals). Although not the core focus of this work, such sociotechnical explorations within and across clusters serve as an opportunity for further investigation and analysis.

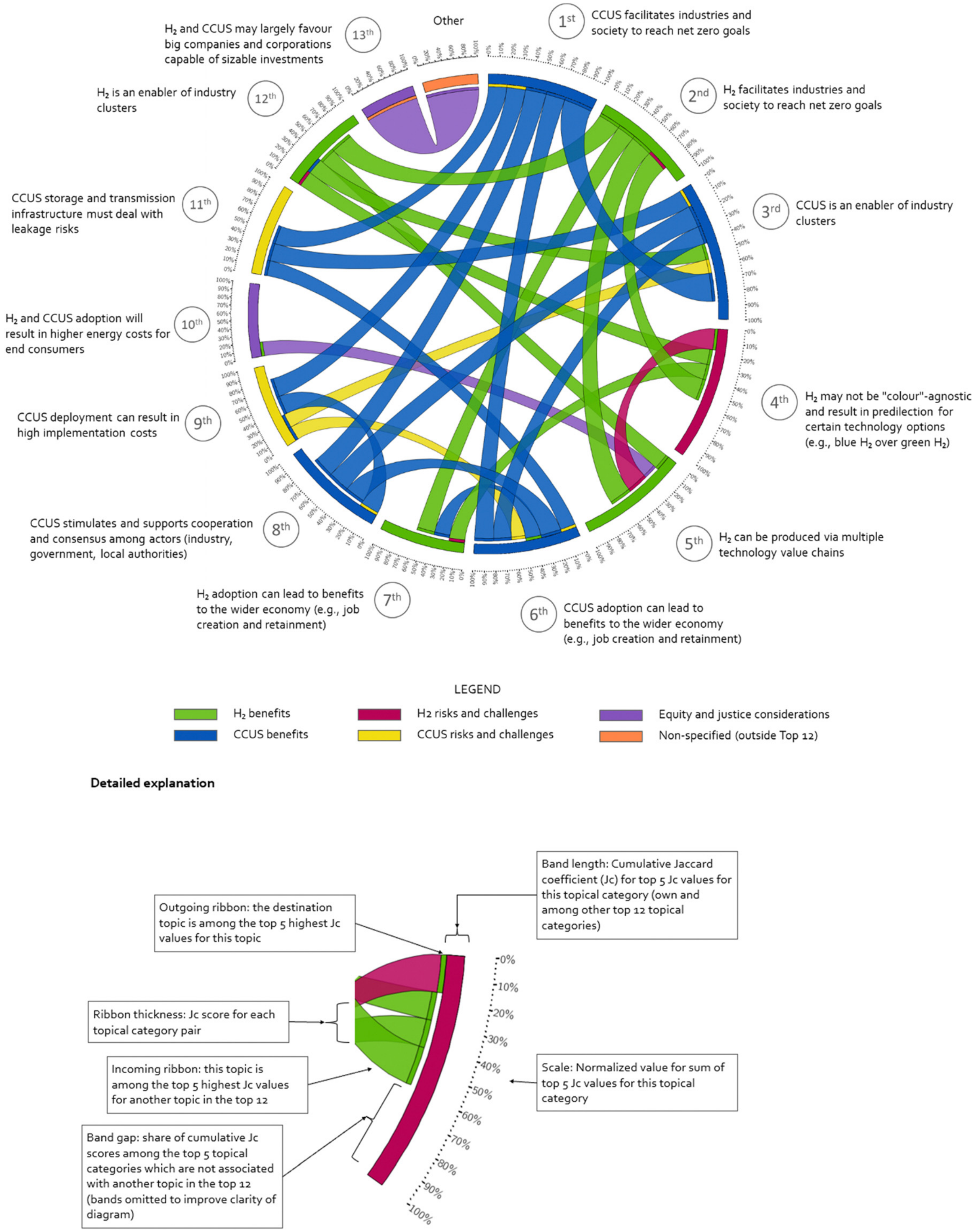

Fig. 5 The most mentioned themes among expert interviews (N = 111) on industrial decarbonization in relation to each other using the Jaccard coefficient measure (J_c). Bands on circumference represent the sum of five largest J_c values among the top 13 themes, while ribbons connect pair-wise themes, with ribbon width representing J_c value. The 13th most mentioned theme has its five highest J_c values with themes outside of the top 12 ("other", orange band). All other ribbons connecting to outside the top 13 are omitted from diagram for clarity.

Our paper, thus, has clear policy implications for different industrial regions. First, we note that while initial costs of technology adoption may be high, leveraging existing infrastructure and value chains from industrial clusters could justify high investments. Our research also highlights the sociotechnical risks associated with industrial clusters, and

Table 8 Themes least discussed among our industrial decarbonization interviews (N = 111)

Rank	Theme
1	H_2 and CCUS may not address lack of diversity in the workforce
2	H_2 production systems may lack sufficient flexibility to adjust to variable electricity supply and demand
3	CCUS *via* mineralisation (CCM) is still under development
4	H_2 infrastructure may face technical challenges due to embrittlement
5	H_2 adoption is a relatively low-cost option for existing natural-gas based furnaces
6	H_2 and CCUS adoption may be distorted by state protectionism towards O&G industry
7	CCUS projects may face lack of cooperation among stakeholders from different clusters
8	CCUS may lack business models to financially support CO_2 permanent storage in geological sites
9	H_2 and CCUS may result in ''offshoring'' of emissions to developing and underdeveloped nations
10	CCUS will be a long-term business and can extend the operational lifetime of current industries (*e.g.*, refining)
11[a]	H_2 can result in cheaper energy prices for end-use consumers
11[a]	CCUS can mitigate other environmental problems, *e.g.*, air pollution
11[a]	H_2 storage in geological formations may not be reliable and result in leakage
11*	CCUS may face lack of sufficient workforce to develop projects
15	CCUS can support the integration of small and medium enterprises (SMEs) in industrial value chains

[a] Note: themes tied according to number of J_d = 1 scores. Source: authors.

while we emphasize the techno-economic challenges emerging from these technologies, such as immature business models and infrastructural challenges, we underscore the importance of addressing socio-cultural concerns. Therefore, we suggest policymakers adopt a holistic approach, fostering collaboration and innovation in business models and policies, with a central commitment to equity, justice, and sustainability and significant stakeholder consultation and engagement. Adopting such an approach could mitigate emerging risks such as sacrifice zones and environmental injustices, which are prevalent concerns in industrial zones globally. By doing so, tangible benefits such as the development of green skills and job opportunities for neighbouring communities can be unlocked. Guaranteeing the commitment to justice and equity in policy decisions while industries decline, evolve and emerge is pivotal in the net-zero transition through H_2 and CCUS in the UK, Europe and globally.

Conflicts of interest

There are no conflicts to declare.

Appendix

IDRIC smart policy and governance interview guide

Warmup question. Tell me/us more about yourself, your background, and how you became interested in net-zero projects.

Technology implementation, experimentation and knowledge. • Where did the idea [for this particular megaproject] come from? Whose idea was it? Who are the lead actors and broader coalitions for each project?

Table 9 Emissions from UK industrial clusters by industry type (data for Fig. 1)

	Industrial emissions by cluster (Mt $CO_{2,eq}$)								
Cluster	Cement	Chemicals	Food and drinks	Iron and steel	Other minerals and metals	Other industry	Pulp and paper	Refining	Total
Grangemouth	—	2.29	0.06	0.03	0.18	0.09	0.01	2.35	5.01
Humber	0.30	0.50	0.04	5.09	0.51	—	—	3.59	10.03
Merseyside	0.55	1.35	0.10	0.06	0.63	0.15	0.27	1.93	5.04
South Wales	0.34	0.02	—	6.08	0.10	0.10	0.06	2.28	8.98
Teesside	—	3.66	0.02	0.11	0.02	—	—	0.01	3.82

Source: data from ref. 58.

Table 10 UK funded industrial decarbonisation activities for each industrial cluster

Cluster	Decarbonisation roadmap	Status	Ref.
Grangemouth	Scotland's Net Zero Roadmap (SNZR)	Published 03/2023	250
Humber	Humber Industrial Decarbonisation Roadmap	Published 03/2023	251
Merseyside	Net Zero North West Cluster Plan 2023	Published 01/2023	252
South Wales	A plan for clean growth	Published 03/2023	253
Teesside	Tess Valley Net Zero Cluster Plan	Published 07/2023	254

Source: authors.

Table 11 Overview of semi-structured expert interview respondents (N = 111)

Code	Institution	Type	Date
R01	BEIS	Policy	10.02.22
R02	University of Manchester, the Tyndall Centre for Climate Change Research	Academia	16.02.22
R03	Equinor ASA	Industry	25.02.22
R04	Wood	Industry; provides technical and industry expertise	28.02.2022
R05	Imperial College London	Academia	2.03.22
R06	Centrica	Industry	3.03.22
R07	VPI Immingham	Industry	4.03.22
R08	ITM Power	Industry	4.03.22
R09	Phillips66	Industry	7.03.22
R10	SSE	Industry	10.03.22
R11*	Triton Power	Industry	16.03.22
R12*	Triton Power	Industry	16.03.22
R13	Humber LEP	Local authorities	17.03.22
R14	Centrica	Industry	18.03.22
R15	VPI Immingham	Industry	18.03.22
R16	Cadent	Industry	8.03.22
R17	University of Sussex	Academia	20.03.22
R18	University of Chester	Academia	21.03.22
R19	Progressive Energy	Industry	21.03.22
R20	University of Chester	Academia	21.03.22
R21	Progressive Energy	Industry	22.03.22
R22	Peel	Industry	22.03.22
R23	North West Business Leadership Team	Industry/Business?	23.03.22
R24	BEIS (ET&CG, Industrial Energy)	Policy	25.03.22
R25	Phillips66	Industry	28.03.22
R26	Progressive Energy	Industry	29.03.22
R27	North Lincolnshire Council	Local authorities	4.04.22
R28	British Steel	Industry	12.04.22
R29	Imperial College London	Academia	12.04.22
R30	Element Energy	Industry	13.04.22
R31	Offshore Renewable Energy Catapult	Industry/Academia (research)	13.04.22
R32*	BEIS	Policy	14.04.22
R33*	BEIS	Policy	14.04.22
R34	Inovyn	Industry	15.04.22
R35	Pilkington	Industry	19.04.22
R36	Encirc	Industry	20.04.22
R37	National Grid	Industry	21.04.22
R38	Hull city council	Local authorities	22.04.22
R39*	SSE	Industry	25.04.22
R40*	SSE	Industry	25.04.22
R41*	SSE	Industry	25.04.22
R42	Mitsubishi Power Europe	Industry	27.04.22
R43	EssarOil	Industry	29.04.22
R44	University of Sheffield, UK CCS Research Centre	Academia	1.04.22
R45	Norwegian British Chamber of Commerce	Industry	26.05.22
R46	Drax	Industry	13.06.22
R47	Manchester University	Academia	17.09.22
R48*	NECCUS	Industry: trade group	22.09.22
R49*	NECCUS	Industry: trade group	22.09.22
R50	Energy Transition Advisor Limited, Storegga	Industry	06.10.22
R51	Herriot-Watt Uni.	Academia	05.10.22
R52	Kellas Midstream	Industry	05.10.22
R53	BGS	Policy-Research-Academia	10.10.22
R54	Lanzatech	Industry	10.10.22
R55	Stanford University	Academia	05.10.22
R56	North Sea Transition Authority	Policy	14.10.22
R57	Wales West Utilities	Industry	21.0.22
R58	SBH4	Industry	24.10.22
R59	ECITB	Trade	24.10.22
R60	Carbon8	Industry	24.10.22
R61	Aker Solutions	Industry	25.10.22
R62	TuvSud	Policy-Research	25.10.22
R63	UCL	Academia	28.10.22
R64	BGS	Policy-Research	27.10.22
R65	ICL, Just Transition Scotland	Academia	26.10.22
R66	SWIC/Industry Wales, Baxter360	Industry	27.10.22
R67	Hydrogen centre/Uni S. Wales	Academia	28.10.22
R68	CT Energy, Southeast Water UK, CPH_2, Nuclear Decommissioning Authority, Cadent Gas Ltd.	Industry	27.10.22

Table 11 (*continued*)

Code	Institution	Type	Date
R69	Tarmac	Industry	28.10.22
R70	University of Strathclyde	Academia	28.10.22
R71	University of Strathclyde	Academia	31.10.22
R72	Plansea	Industry	31.10.22
R73	Manchester Uni.	Academia	31.10.22
R74	Aker Solutions	Industry	24.10.22
R75	Carbon Trust	Policy	03.11.22
R76	Storegga	Industry	03.11.22
R77	Renewables hydrogen alliance	Policy	09.11.22
R78	Just Transitions Committee, Uni. Bath	Academia	09.11.22
R79	Airhive	Industry	10.11.22
R80	Engaging Next Gen. Industry, Fuel Change	Trade	10.11.22
R81	University of Aberdeen	Academia	28.10.22
R82	Reliagen, Association of Renewable Energy and Clean Technology, BioSci	Industry	10.11.22
R83	Suez Group	Industry	11.11.22
R84	Shell	Industry	11.11.22
R85	Green alliance	Policy	09.11.22
R86	SCCS	Policy	14.11.22
R87	Vale	Industry	31.01.23
R88	Storegga (Pale Blue Dot)	Industry	14.11.22
R89	Tees Valley CA, CER Technologies, Ltd	Local authorities	08.11.22
R90	ENSUS UK Ltd, NEPIC	Trade	15.11.22
R91	Innovate UK (Enterprise Services at Heriot-Watt)	Policy-Research	16.11.22
R92	VNZS, VItaBio Group	Industry	07.11.22
R93	Oxford	Academia	16.11.22
R94	British Geological Survey	Policy-Research	18.11.22
R95	Edinburgh University	Academia	18.11.22
R96	Honeywell	Industry	18.11.22
R97	Sheffield University	Academia	18.11.22
R98	BEIS (NZBI – Clean Heat)	Policy	15.11.22
R99	Low Carbon Contracts Company	Policy-Industry	24.11.22
R100	Shell	Industry	25.11.22
R101	Intercontinental Energy, Everything About Hydrogen, Hydrogen Council, Sustainable Energy Council	Industry	25.11.22
R102	Scottish Parliament	Policy	02.12.22
R103	British Geological Survey	Academic/Research/Industry	06.12.22
R104	Durham University	Academia	09.12.22
R105	Retired British Steel	Industry	16.12.22
R106	Helmholtz Centre, RIFS-Potsdam	Academia	
R107	BEIS	Policy	07.12.22
R108	Kellas Midstream (NEPIC)	Industry	22.12.22
R109	Sembcorp Energy UK (Wilton Int.)	Industry	11.01.23
R110	RWE	Industry	15.12.22
R111	Protium Green Solutions, Everything About Hydrogen (UK Hydrogen & Fuel Cell Association)	Industry	19.01.23

Source: authors. Note: * denotes a group interview.

Table 12 Key references used as the starting point for literature search using a snowballing approach coupled with manual search of databases

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Source: authors.

Table 13 Detailed thematic and narrative trends on the benefits of H_2 deployment

Type	Benefits	Interview mentions #	Interview mentions %	Overall rank	Jaccard coefficient Mean	Jaccard coefficient Median
Economic	H_2 adoption can lead to benefits to the wider economy (*e.g.*, job creation and retainment)	41	36.9	7	0.4306	0.1793
	H_2 can be used in multiple markets *via* chemical energy carriers (*e.g.*, ammonia, methanol)	32	28.8	21	0.4074	0.1556
	H_2 will be a long-term business and can extend the operational lifetime of current industries (*e.g.*, refining)	16	14.4	84	0.3871	0.1189
	H_2 can create opportunities across economic sectors ("hydrogen economy")	13	11.7	100	0.3333	0.0883
	H_2 can help avoid stranded assets	9	8.1	119	0.2222	0.0842
	H_2 adoption is a relatively low-cost option for existing natural-gas based furnaces	6	5.4	128	0.2500	0.0578
Socio-cultural	H_2 stimulates and supports cooperation and consensus among actors (industry, government, local authorities)	37	33.3	14	0.4762	0.1622
	H_2 adoption encourages broad innovation (technologies, practices and business models)	20	18.0	67	0.3061	0.1249
	H_2 can leverage public consultations and engagements to elicit public support and participation	17	15.3	79	0.3182	0.1096
	H_2 requirements for trained/skilled staff can be met by existing industries and initiatives	17	15.3	79	0.3429	0.1171
	H_2 can result in cheaper energy prices for end-use consumers	7	6.3	126	0.3000	0.0752
Political	H_2 can increase the competitiveness of industries both nationally and internationally	29	26.1	27	0.4000	0.1607
	H_2 can enhance energy security and energy independence of nations	27	24.3	33	0.4000	0.1489
	H_2 production enjoys political and policy support	25	22.5	44	0.4762	0.1387
Geographic and environmental	H_2 can leverage geographical proximity of industries and demand centres to expedite adoption	29	26.1	27	0.4286	0.1523
	H_2 can mitigate other environmental problems, *e.g.*, air pollution	10	9.0	113	0.2273	0.0714
	H_2 standards (*e.g.*, classification as low-carbon H_2) can be used to enforce stringent CO_2 reduction targets	10	9.0	113	0.2500	0.0863
Technical	H_2 can be produced *via* multiple technology value chains	44	39.6	5	0.5362	0.1800
	H_2 can reuse infrastructure that is already available	31	27.9	23	0.4286	0.1485
	H_2 production *via* conventional technologies is at high TRL	22	19.8	60	0.3171	0.1213
	H_2 can help decarbonise other sectors, *e.g.*, domestic heating	22	19.8	60	0.3500	0.1455
	H_2 can provide flexibility to electricity and power systems as an energy storage medium	21	18.9	65	0.3714	0.1460
	H_2 can support fuel switching in industry	17	15.3	79	0.3200	0.1208

Source: authors.

Table 14 Detailed thematic and narrative trends on the benefits of CCUS deployment

Type	Benefits	Interview mentions #	Interview mentions %	Overall rank	Jaccard coefficient Mean	Jaccard coefficient Median
Economic	CCUS adoption can lead to benefits to the wider economy (*e.g.*, job creation and retainment)	44	39.6	5	0.4306	0.1793
	CCUS adoption can be economically self-sufficient or cost-effective	16	14.4	84	0.4074	0.1556
	CCUS can support the integration of small and medium enterprises (SMEs) in industrial value chains	11	9.9	110	0.3871	0.1189
	CCUS will be a long-term business and can extend the operational lifetime of current industries (*e.g.*, refining)	9	8.1	119	0.3333	0.0883
Socio-cultural	CCUS stimulates and supports cooperation and consensus among actors (industry, government, local authorities)	41	36.9	7	0.2222	0.0842
	CCUS adoption encourages broad innovation (technologies, practices and business models)	27	24.3	33	0.2500	0.0578
	CCUS requirements for trained/skilled staff can be met by existing industries and initiatives	15	13.5	89	0.4762	0.1622
	CCUS can leverage public consultations and engagements to elicit public support and participation	11	9.9	110	0.3061	0.1249
Political	CCUS can increase the competitiveness of industries both nationally and internationally	22	19.8	60	0.3182	0.1096
	CCUS enjoys political and policy support	26	23.4	38	0.3429	0.1171
	CCUS actors can instilled confidence and trust in institutional support	16	14.4	84	0.3000	0.0752
	CCUS can enhance energy security and energy independence of nations	13	11.7	100	0.4000	0.1607
Geographic and environmental	CCUS can leverage geographical proximity of industries and demand centres to expedite adoption	37	33.3	14	0.4000	0.1489
	CCUS enables negative emissions technologies	23	20.7	55	0.4762	0.1387
	CCUS can support the integration of renewable energy sources	14	12.6	95	0.4286	0.1523
	CCUS can mitigate other environmental problems, *e.g.*, air pollution	8	7.2	122	0.2273	0.0714
Technical	CCUS can reuse infrastructure that is already available	26	23.4	38	0.2500	0.0863
	CCUS technologies are at high TRL	26	23.4	38	0.5362	0.1800
	CCUS is a key technology to enable blue H_2 adoption	27	24.3	33	0.4286	0.1485
	CCUS enables the adoption of DAC technologies	12	10.8	106	0.3171	0.1213

Source: authors.

Table 15 Detailed thematic and narrative trends on the challenges of H_2 deployment

Type	Challenges	Interview mentions #	Interview mentions %	Overall rank	Jaccard coefficient Mean	Jaccard coefficient Median
Economic	H_2 deployment can result in high implementation costs	37	33.3	14	0.4200	0.1637
	H_2 projects may lack clear business models to justify investment	35	31.5	19	0.4130	0.1668
	H_2 investment may be delayed due to future market uncertainties	30	27.0	25	0.4130	0.1585
	H_2 may not have clear end users and market demand to stimulate investments from potential producers	16	14.4	84	0.2727	0.1069
	H_2 projects may be unable to forecast profitability of operations due to uncertainties in demand markets	14	12.6	95	0.3000	0.1167
	H_2 adoption may be hindered due to lack of incentives to deployment	12	10.8	106	0.2727	0.0968
Socio-cultural	H_2 projects may suffer from "spillover" lack of trust in O&G industry from end consumers	20	18.0	67	0.3000	0.1246
	H_2 may face opposition from local stakeholders (*i.e.*, "not-in-my-backyard" phenomenon, or NIMBY)	13	11.7	100	0.3333	0.1078
	H_2 adoption will require replacement of boilers	12	10.8	106	0.2800	0.0832
	H_2 may face lack of sufficient workforce (*e.g.*, construction) to develop projects	12	10.8	106	0.2941	0.1079
	H_2 may face lack of sufficiently trained workforce	10	9.0	113	0.3529	0.0869
Political	H_2 projects may face tensions due to competition among companies for funding and resources	30	27.0	25	0.4048	0.1790
	H_2 may be delayed due to bureaucracy and lack of political action	29	26.1	27	0.5588	0.1678
	H_2 may be hindered by lack of continuity in political action and of harmonization in policy strategies	24	21.6	50	0.5588	0.1517
	H_2 may not receive sufficient government support	24	21.6	50	0.3488	0.1217
	H_2 may suffer from lacking regulatory frameworks	23	20.7	55	0.3571	0.1126
	H_2 projects may face collateral effects from geopolitical tensions	20	18.0	67	0.5217	0.1313
	H_2 face uncertainties concerning the true scale and magnitude of feasible projects	18	16.2	75	0.2791	0.1164
		17	15.3	79	0.3125	0.1230

Table 15 (*continued*)

Type	Challenges	Interview mentions #	Interview mentions %	Overall rank	Jaccard coefficient Mean	Jaccard coefficient Median
	H_2 may be hindered by mixed signals and wrong messaging resulting from misaligned policy action					
	H_2 investment decisions may be delayed by lack of political stability at the national government level	17	15.3	79	0.4231	0.1026
	H_2 storage does not have specific policy frameworks to support it	15	13.5	89	0.3333	0.1149
	H_2 projects may face governability challenges from lack of clear governmental guidelines	15	13.5	89	0.5217	0.1172
	H_2 development may not be developed in a timely manner and face project delays	15	13.5	89	0.2800	0.1062
Environmental	H_2 may not be "colour"-agnostic and result in predilection for certain technology options (*e.g.*, blue H_2 over green H_2)	47	42.3	4	0.5273	0.1919
	H_2 may be opposed by end consumers as it is seen as allowing the O&G industry to keep operating as usual	25	22.5	44	0.4000	0.1572
	H_2 may not address process emissions from certain industries and activities	20	18.0	67	0.3235	0.1305
	H_2 systems where purity is necessary cannot leverage blended distribution infrastructure (*i.e.*, with natural gas)	6	5.4	128	0.3333	0.0682
Technical	H_2 adoption will require wide-scale infrastructure changes	37	33.3	14	0.5273	0.1784
	H_2 storage and transmission infrastructure must deal with leakage risks	36	32.4	18	0.4600	0.1724
	H_2 supply security is threatened by variability of intermittent renewable energy sources	34	30.6	20	0.4200	0.1529
	H_2 may lead to safety risks	25	22.5	44	0.3415	0.1389
	H_2 technologies are still in the early stages of development (low TRL)	22	19.8	60	0.4048	0.1340
	H_2 fuel switching opportunities may be limited depending on the industry	14	12.6	95	0.3000	0.1096
	H_2 technologies may not be sufficiently proven at commercial scale	13	11.7	100	0.5000	0.1010
	H_2 has different chemical properties (*e.g.*, flame velocity, calorific value) from other gaseous fuels	10	9.0	113	0.2500	0.0842
	H_2 production and use may be less energy efficient than direct electrification	9	8.1	119	0.4286	0.0824
	H_2 storage in geological formations may not be reliable and result in leakage	8	7.2	122	0.5000	0.0772
	H_2 infrastructure may face technical challenges due to embrittlement	4	3.6	131	0.2308	0.0374
	H_2 production systems may lack sufficient flexibility to adjust to variable electricity supply and demand	1	0.9	135	0.1111	0.0208

Source: authors.

Table 16 Detailed thematic and narrative trends on the challenges of CCUS deployment

Type	Challenges	Interview mentions #	Interview mentions %	Overall rank	Jaccard coefficient Mean	Jaccard coefficient Median
Economic	CCUS deployment can result in high implementation costs	40	36.0	9	0.4200	0.1637
	CCUS projects may lack clear business models to justify investment	28	25.2	31	0.4130	0.1668
	CCUS projects may be unable to forecast profitability of operations due to uncertainties in demand markets	27	24.3	33	0.4130	0.1585
	CCUS may not be viable without appropriate carbon pricing mechanism	23	20.7	55	0.2727	0.1069
	CCUS is hindered by a lack of clear markets for high-quality GHG removal credits	15	13.5	89	0.3000	0.1167
	CCUS subsidies may hinder the development of other projects needed for clean energy transition	10	9.0	113	0.2727	0.0968
	CCUS may lack business models to financially support CO_2 permanent storage in geological sites	8	7.2	122	0.3000	0.1246
Socio-cultural	CCUS projects may suffer from "spillover" lack of trust in O&G industry from end consumers	28	25.2	31	0.3333	0.1078
	CCUS may face opposition from local stakeholders (*i.e.*, "not-in-my-backyard" phenomenon, or NIMBY)	13	11.7	100	0.2800	0.0832
	CCUS may face lack of sufficiently trained workforce	13	11.7	100	0.2941	0.1079
	CCUS may face lack of sufficient workforce to develop projects	7	6.3	126	0.3529	0.0869
Political	CCUS stakeholders may be unaligned and communicating poorly	26	23.4	38	0.4048	0.1790
	CCUS may not receive sufficient government support	25	22.5	44	0.5588	0.1678
	CCUS projects may face tensions due to competition among companies for funding and resources	25	22.5	44	0.5588	0.1517
	CCUS may be delayed due to bureaucracy and lack of political action	24	21.6	50	0.3488	0.1217
	CCUS may be hindered by lack of continuity in political action and of harmonization in policy strategies	14	12.6	95	0.3571	0.1126
		20	18.0	67	0.5217	0.1313

Table 16 (*continued*)

Type	Challenges	Interview mentions #	Interview mentions %	Overall rank	Jaccard coefficient Mean	Jaccard coefficient Median
	CCUS investment decisions may be delayed by lack of political stability at the national government level					
	CCUS may face uncertainties concerning the true scale and magnitude of feasible projects	16	14.4	84	0.2791	0.1164
	CCUS may suffer from lacking regulatory frameworks	15	13.5	89	0.3125	0.1230
	CCUS may be hindered by lack of continuity in political action and of harmonization in policy strategies	14	12.6	95	0.4231	0.1026
	CCUS projects may face lack of cooperation among stakeholders from different clusters	4	3.6	131	0.3333	0.1149
Environmental	CCUS may be opposed by end consumers as it is seen as allowing the O&G industry to keep operating as usual	27	24.3	33	0.5217	0.1172
	CCUS with biomass (BECCS) may result in additional environmental impacts	25	22.5	44	0.2800	0.1062
	CCUS does not address other non-carbon emissions, *e.g.*, NO_x and SO_x	24	21.6	50	0.5273	0.1919
	CCUS projects may fail to meet climate targets	18	16.2	75	0.4000	0.1572
Technical	CCUS storage and transmission infrastructure must deal with leakage risks	39	35.1	11	0.3235	0.1305
	CCUS deployment may be limited by physical constraints on CO_2 storage (*e.g.*, geological)	29	26.1	27	0.3333	0.0682
	CCUS technologies may not be sufficiently proven at commercial scale	26	23.4	38	0.5273	0.1784
	CCUS may be hindered by uncertainties in geological storage sites	24	21.6	50	0.4600	0.1724
	CCUS will require massive infrastructure for transmission and transport of expected CO_2 volumes	23	20.7	55	0.4200	0.1529
	CCUS may not have clear application opportunities for CO_2 emissions, limiting CCU deployment	18	16.2	75	0.3415	0.1389
	CCUS *via* mineralisation (CCM) is still under development	3	2.7	134	0.4048	0.1340

Source: authors.

Table 17 Detailed thematic and narrative trends concerning justice and equity considerations

Type	Themes	Interview mentions #	Interview mentions %	Overall rank	Jaccard coefficient Mean	Jaccard coefficient Median
Justice and equity considerations	H_2 and CCUS adoption will result in higher energy costs for end consumers	40	36.0	9	0.4306	0.1793
	H_2 and CCUS may largely favour big companies and corporations capable of sizable investments	38	34.2	12	0.4074	0.1556
	H_2 and CCUS adoption may erode demand for traditional workforce and eliminate jobs	31	27.9	23	0.3871	0.1189
	H_2 and CCUS infrastructure costs will be partially borne by end users	26	23.4	38	0.3333	0.0883
	H_2 and CCUS projects may lead to outsourcing of jobs due to required highly skilled personnel available elsewhere	23	20.7	55	0.2222	0.0842
	H_2 and CCUS development may be influenced by lobbying efforts from O&G industry	22	19.8	60	0.2500	0.0578
	H_2 and CCUS projects may promote environmental injustices	19	17.1	72	0.4762	0.1622
	H_2 and CCUS are seen as "greenwashing" technologies to support O&G industry towards "business-as-usual"	19	17.1	72	0.3061	0.1249
	H_2 and CCUS additional costs may disproportionally impact low-income end consumers	18	16.2	75	0.3182	0.1096
	H_2 and CCUS projects may not address unemployment affecting local communities due to mismatch in job skills	14	12.6	95	0.3429	0.1171
	H_2 and CCUS are not supported by heavy industries to the same extent that profit-generating activities are	11	9.9	110	0.3000	0.0752
	H_2 and CCUS adoption to replace natural gas will burden end users with costs associated with equipment changes	10	9.0	113	0.4000	0.1607
	H_2 and CCUS projects can distort local job markets and exacerbate income inequality in local communities	8	7.2	122	0.4000	0.1489
	H_2 and CCUS adoption may be distorted by state protectionism towards O&G industry	5	4.5	130	0.4762	0.1387
	H_2 and CCUS may result in "offshoring" of emissions to developing and underdeveloped nations	4	3.6	131	0.4286	0.1523
	H_2 and CCUS may not address lack of diversity in the workforce	1	0.9	135	0.2273	0.0714

Source: authors.

Table 18 The economic benefits of hydrogen (n = 111)

Theme	Rank	Frequency by interview		Participant code	Representative quote
Benefits to the economy (*i.e.* job creation and job retainment)	1	41	36.93%	R65	*I think one of the interests that there has been in industrial CCS and hydrogen is that it has been a way of protecting employment. It gives people who've operated in the oil and gas sector a place to go because many skills are similar.*
Multiple markets (*i.e.* transport, maritime and rails)	2	32	28.82%	R21	*I guess the benefits are, from a vehicle perspective, range* [when compared with battery electric vehicles – EVs]*. You can fill a tank of hydrogen, it can run your vehicle for 500 miles instead of 150, and you can refuel in 5 minutes as opposed to half an hour or an hour* [for EVs]*. Sounds like a more attractive business model than EVs.*
Long term operations and longevity	3	16	14.41%	R43	*The integration with the oil refinery makes it extra special because it increases the longevity of the oil refinery business, which is profitable.* [...] *Yes, you make money on the hydrogen; you make money on the refinery.*
Building a hydrogen economy	4	14	12.61%	R14	*All the projects, a lot of them, are interlinked, but even if you think about the supply chain, everyone needs the same level of technology readiness; everyone needs very similar technology to be available on the shelf to then go to vendors and get the right equipment, whether that be compression or pumps or whatever. This is why we are building the hydrogen economy.*
Avoids stranded assets	5	10	9%	R11	*There's a risk that there's a lot of gas out there that becomes stranded and a lot of energy that becomes stranded, because you don't want to release the* CO_2. [...] *So, in that area, blue hydrogen could help a lot. It avoids stranded assets.*
Low cost for retrofitting existing industrial infrastructure	6	7	6.30%	R35	*During the trials, we were able to transfer the furnace from natural gas to hydrogen at a relatively low cost, certainly less than £1 million. This cost was not significant for us.*

Source: authors.

Table 19 The socio-cultural benefits of hydrogen (n = 111)

Theme	Rank	Frequency by interview		Participant code	Representative quote
Cooperation and knowledge exchange	1	38	34.23%	R27	*The other bit is around collaboration. I suppose you'd call it a consortium. You'd try to bring together, working collectively on it, the hydrogen producers, maybe the hydrogen vehicle manufacturers, and then the end users so there's a collaboration so it brings it all together, so there's that hub feeling to it. Everyone is working in the same direction.*
Encourages innovation, technology development and business models	2	21	18.91%	R75	*This plant doesn't exist in the world at the moment. So, even though the process is mature, this is like combining A and B. A and B exist already; suddenly, you put them together, and you have a new thing, right?* [...] *It is not radically innovative, but there is an innovation element of it. There's also a new product and possibly a new business model.*
Enables public participation and public acceptance	3	18	16.21%	R10	*We are engaged with the local community; public acceptance and participation are key to developing the project. In doing so,* [we] *tell a story of how it is not just a technical project but also a socio-economic project for the region and the cluster in general, so about the creation of jobs, health benefits and how it brings supply chain opportunities that will be unlocked for the region. We tell a story of how their participation enables this to happen.*
Trained workforce	4	17	15.31%	R19	*None of this technology is massively complicated. The chemical industry, the oil and gas industry, and the gas industry combined actually have the majority of the skills we need already.*
Offers cheaper energy prices to consumers	5	8	7.20%	R46	*In some years, hydrogen could become a cheaper energy option for energy consumers. Not now, but in some years, the future might see hydrogen becoming a more affordable energy choice for consumers.*

Source: authors.

Table 20 The political benefits of hydrogen (n = 111)

Theme	Rank	Frequency by interview		Participant code	Representative quote
Increases national competitiveness	1	30	27.02%	R30	*If we don't decarbonize at some point, our industries are not going to be competitive, particularly in some of the large markets. We're not going to be able to keep those jobs and those skills around. Equally, suppose we put too much pressure on the industry to decarbonize and it's too expensive. In that case, industries will no longer be competitive on an international market and simply move their organizations elsewhere. So maybe there's a wider strategy here? That's why we need to be extra competitive.*
Enhances energy security and independence	2	27	24.32%	R82	[The government] *must encourage regional hubs for green hydrogen production, delivery and storage. So, there could be hubs to inject it in a controlled way to blend natural gas on the gas grid and reduce our reliance on Russia and overseas imports but to a safe level where people's boilers can still work. This is a safe way to achieve energy security and comply with climate targets.*
Political and policy support	3	26	23.42%	R71	*The UK has prioritized policies and initiatives to support hydrogen development and implementation. You can see this in their policy reports, climate targets and funding calls.*

Source: authors.

Table 21 The geographic and environmental benefits of hydrogen (n = 111)

Theme	Rank	Frequency by interview		Participant code	Representative quote
Geography of the project	1	29	26.12%	R14	*It all makes sense as well in terms of geographical location and the amount of industry. The proximity of industrial clusters allows sharing of resources and infrastructure, making* [them] *more efficient and cost-effective.*
Mitigates other environmental problems	2	11	9.90%	R5	*I think that hydrogen could also mitigate other environmental issues; it is cleaner than carbon*[-based] *and other fuels, so it also helps provide society with cleaner air.*
Stringent targets for carbon emissions	3	10	9%	R37	*So the standards are on hydrogen, specifications of what is low-carbon hydrogen, purity, pressure and temperature. And again, I think the very recent documents that came out are interesting to see* [how] *what classifies as low-carbon hydrogen is defined. I think the 20 grammes of CO_2 per megajoule is quite a stringent target.*

Source: authors.

Table 22 The technical benefits of hydrogen (n = 111)

Theme	Rank	Frequency by interview		Participant code	Representative quote
Different sources of hydrogen (blended hydrogen)	1	44	36.93%	R31	*They plan to produce hydrogen from the reformation of natural gas, so-called blue hydrogen, and supply that to industry, and the carbon will be captured and stored in the CCS part of the project. There are other types of hydrogen, for instance, green hydrogen, which is generated by renewable energy. Another one is pink hydrogen, which is powered by nuclear energy. However, the last two may take a bit longer to fully consolidate.*
Infrastructure already available	2	32	28.82%	R16	*One of the messages that we're keen to get across is that one of the benefits of hydrogen is that you can reuse a lot of the infrastructure that's there already, not all of it, and you will still need to build new pipes. But some of it is-you can repurpose the pipes and the infrastructure would already be there.*
High Technology Readiness Level (TRL)	3	23	20.72%	R34	*We've been producing hydrogen for 100 years, literally 100 years. That hydrogen we use on site. We burn it in a boiler to produce steam and use it for chemical manufacture like HCL and hydrogen peroxide.*
Domestic heating	3	23	20.72%	R38	*We did a hydrogen piece of work with Equinor, Leeds City Council, Bradford, and Teesside, to look at what's the role for the hydrogen within this side of the UK. That showed that we could use hydrogen to replace heating within homes, as part of that transition. Obviously, Northern Gas Networks are quite keen on that. They've done a lot of testing of equipment to make sure that it works, and it doesn't leak.*
Flexibility for energy storage	4	22	19.81%	R26	*One of the big challenges of going down the road of more and more and more renewables is we're more and more susceptible to the intermittency of renewables. What hydrogen allows us to do is store some of that energy however it's being created and then release it back for gas turbines to turn into electricity when the grid requires it. That's a significant component of HyNet as well, because we're going to generate storage, and we have off-takers who will be combined cycle gas turbines to convert into electricity.*
Fuel switching	5	18	16.21%	R35	*Actually, we're quite used to using different fuels and switching. A float furnace, to make glass, is a 24/7 365 process and they run for 15 years or maybe even a little bit longer than that. We cannot stop that process. If you do, then the temperature drops, and you start to cause major problems to the furnace. We have to have backup systems and things like that. So, switching between fuels is something that we can do quite easily. Yes, the investment is not huge but, you're right, we still need to make a decision on which of those fuels we will use and that really will depend on the technical feasibility. We have confidence in hydrogen.*

Source: authors.

Table 23 The economic benefits of CCUS (n = 111)

Theme	Rank	Frequency by interview		Participant code	Representative quote
Benefits to the economy (*i.e.* job creation and job retainment)	1	42	37.83%	R60	*The main thing about that is the jobs being generated are going to be in areas that, to be frank, need regeneration. Like Teesside and the northeast and the northwest as well. And south Wales as well. It just happens that all these industrialized areas, for obvious reasons, these industrialized areas are the ones that need rejuvenation. That's exactly what these projects are about.*
Economically self-sufficient	2	16	14.41%	R96	*CCUS is an excellent business model. It can pay for itself by selling CO_2 to make products or using it to produce energy. Companies could also get money from the government by mitigating emissions. Cashback.*
Allows the integration of small and medium enterprises in new business models	3	11	9.90%	R76	*Integrating SMEs is a great way of attracting investment. It cements the UK's place in terms of leadership on climate change and the green economy more widely. It sends very strong signals the UK is taking it seriously and doing all the right things. Exploring all the right options is the way to do this.*
Long term operations	4	10	9.09%	R13	*Because businesses will say, "What happens in year six?" They are not putting the capital kit on the ground for five years. They are placing capital kits on the ground for thirty to fifty years, possibly more. They will need to have some sort of visibility of how that might emerge or evolve going forwards. CCUS could offer true long-term benefits.*

Source: authors.

Table 24 The socio-cultural benefits of CCUS (n = 111)

Theme	Rank	Frequency by interview		Participant code	Representative quote
Cooperation and knowledge exchange	1	41	36.93%	R7	*Both industry and government are kind of aligned in that sense, and there is international clamour, of course, for everyone to take action concerning climate change. So, the overall trajectory is that responsible businesses should respond to make this happen. so, it's a combination of things. Everybody is pushing in the same direction.*
Encourages innovation, technology development and business models	2	27	24.32%	R64	*[Carbon] utilization is a new one, and lots of chemical engineers get involved in it because it's probably one of the most palatable ones for funding and also a market and capitalist economy because it's trying to answer an issue with a profitable solution so that you can open a business, you can transform the project into something. Whereas permanent storage just doesn't make any profit*
Trained workforce	3	15	13.51%	R65	*If you're looking at carbon storage, the geological skills in the oil and gas industry can then be redeployed for the carbon storage part of the chain. So, I think that's where a lot of the interest is coming from, and why you see bodies like what used to be called the 'Oil and Gas Technology Centre' in Aberdeen becoming the 'Net Zero Technology Centre', for example, thinking about net zero in the North Sea. The UK Oil and Gas Authority has become the North Sea Transition Authority. All of these kinds of symbolic changes are that organizations whose skill base is rooted in the oil and gas chain are now trying to repurpose themselves for a broader picture. Hydrogen and CCUSS, are absolutely part of that.*
Enables public participation and public acceptance	4	11	9.90%	R13	*I wasn't aware that BEIS, for example, as part of their policy setting, were engaging lots of community groups, the TUC, the Friends of the Earth, whoever. But absolutely, communities are hugely important in terms of how this will roll out in the Humber or any other cluster for that matter. We are engaged with them, and we encourage them to be actively involved in the project*

Source: authors.

Table 25 The political benefits of CCUS (n = 111)

Theme	Rank	Frequency by interview		Participant code	Representative quote
Increases national competitiveness	1	26	23.42%	R67	*We want to stay competitive. That's the mission of the South Wales Cluster, to decarbonize, to utilize our resource more efficiently, but also to ensure that we maintain the competitiveness of the industry.*
Political and policy support	2	22	19.81%	R79	*At the minute, BEIS has funded some removals innovators. There was Rolls Royce, Heriot-Watt, and one of the pure DAC start-ups, Mission Zero. Each got hundreds of thousands, maybe the low millions, for some kind of demonstration plants. You can see that Industry and government are very supportive of this technology.*
Trust in the project and technology	3	16	14.41	R4	*I'm more confident today than I was two–three years ago. I think the government has made significant progress in terms of instilling some kind of confidence in the industry, that the government's actions to date have suggested a different approach and a level of seriousness has been demonstrated. So, the industry is in a place where there's so much belief that this time around the government will definitely push this through. There's trust that unlike other times, where the project simply did not go through.*
Enhances energy security and independence	4	13	11.71%	R81	*So, it's risk, risk, risk, let's understand the risk. But to understand the risks you have to understand the benefits as well, what is the benefit of carbon capture? What's carbon capture going to bring to us? It might help with energy security, that's one of their key benefits.*

Source: authors.

Table 26 The geographic and environmental benefits of CCUS (n = 111)

Theme	Rank	Frequency by interview		Participant code	Representative quote
Geography of the project	1	37	33.33%	R103	*There's access to the North Sea which has got a large concentration of possible carbon capture storage sites. Yes, in terms of geography, the refinery and the Humber area should be one of the first places to deploy carbon capture just because of the advantages in terms of carbon capture stores and industry present. There're possibilities for shipping as well, being so close to major ports. In terms of geographical location, I think there are a lot of advantages.*
Enables negative emissions	2	23	20.72%	R29	*If you want to get to net zero, you need some offsets, so you need to make, for example, bio-based hydrogen with CCS, so carbon-negative hydrogen, or carbon-negative electricity, or some other direct air capture or something. You can't go to net zero just by abating emissions. You need some offsets as well, because it's impossible to remove every emission from the cluster. So, if you want a net zero cluster, probably 10%, 20% of the emissions will have to be dealt with by technologies that enable negative emissions.*
Allows the integration of renewables	3	14	12.1%	R40	*We're basically there to act as a normal combined cycle gas turbine does now, it's to balance supply and demand again. Actually, by building that, you're enabling a greater rollout of renewables because you're actually providing those services to make sure that, with a high penetration of renewables, you can still have a robust, secure, energy system that's operable. We're providing that flexibility.*
Mitigate other environmental problems	4	8	7.22%	R54	*If we just take an example of vulnerable groups with respiratory illness, for example, it has a very positive impact, because you're no longer emitting carbon and the associated pollutants from a point source, for example, like a steel mill, or if you have an incineration or trash-to-energy plant, for example. So, the benefits are real, because you're reducing the particulate emissions, pollutants, and CO_2.*

Source: authors.

Table 27 The technical benefits of CCUS (n = 111)

Theme	Rank	Frequency by interview		Participant code	Representative quote
Infrastructure already available	1	27	24.32%	R84	*One of the key value propositions that we see is that you want to reuse existing infrastructure. So we want to reuse the offshore Goldeneye pipeline, we want to reuse the offshore Miller pipeline, we want to reuse the onshore Feeder 10 pipeline, so there is an element there and a link to the decommissioning programmes.*
High TRL	2	26	23.42%	R1	*CO_2 has been transported and stored in the past 20 years point. So they've been doing it for a long time. CO_2 pipelines in North America have been operated for more than a decade. We have CO_2 capture, well, the first patents here to capture were in the 1930s; we have CO_2 capture on every town gas facility in the UK, it does not need to be demonstrated the feasibility of this technology.*
Enables blue hydrogen	2	26	23.42%	R26	*Blue hydrogen allows us to take natural gas continuously and convert it into hydrogen continuously, so we get very, very high utilization of invested assets. We can supply the hydrogen continuously, which is what industry needs, and we can do it at really large scale. Our very first plant will be 350 megawatts, our second plant will be twice that size, 700.*
Enables DAC	3	12	10.81%	R79	*But we're not talking about novel, physical, chemical reactions or new advanced synthetic sorbents which is where some of the DAC companies are placing their focus. For us, it's process re-engineering with some important novel-so the application of high temperature. Actually, some recent scientific advances in CCS but applying them to DAC to direct air capture. People accept that if you're a direct air capture company, you don't need to have the storage in place because it's so difficult to have it in place. You probably do need to have someone utilize it. It's quite useful for early revenues until the storage shows up.*

Source: authors.

Table 28 The economic challenges of hydrogen (n = 111)

Theme	Rank	Frequency by interview		Participant code	Representative quote
The high costs of hydrogen deployment	1	37	33.33%	R35	*The business case is yet to be fully defined, but we expect the price of hydrogen to be similar to natural gas plus carbon; that is really what's keeping us interested in this. If we're looking at a business case where hydrogen is natural gas plus carbon plus 50%, then we cannot add that to our fuel bill, which is huge, as I'm sure you can imagine.*
Inappropriate business models	2	35	31.33%	R34	*The company where I work is private. It's a commercial company, it has its own ambitions for net zero, but it's not a charity; it's not going to just build for the sake of it. It needs a strong business case, and it will put its money where the best case is; right now that's not the UK.*
Future market uncertainties	3	31	27.92%	R14	*We have asked the government for a regulatory framework and a regulatory backstop to mitigate future uncertainties, something like a cap and flow model or something that you would use for infrastructure to support that investment. And, again, it is not just Centrica asking for this; everybody will be in the same position. And if the Government and BEIS want hydrogen storage, they will need to come up with this framework because, otherwise, it will delay the investment in projects.*
Lack of market	4	16	14.41%	R84	

Table 28 (*continued*)

Theme	Rank	Frequency by interview		Participant code	Representative quote
Uncertain profitability	5	14	12.61%	R103	*For me, the key challenge with hydrogen is actually who is going to use the hydrogen. I can build a hydrogen plant, but I've got no users so that's a bit useless. Again, you need to build that supply and demand at the same time.* *[It] doesn't seem to be a big demand for hydrogen at the moment. Companies can generate hydrogen and make hydrogen. They can store it. It's whether or not they can get the user community there to actually use hydrogen in suitable volumes, I suppose. It's not just, "Have we got storage? Have we got generation? Have we got a user?" They all need to happen together, and that can be quite difficult.*
Lack of incentives to deploy the technology	6	12	10.81%	R34	*I said, we're building green hydrogen production in Norway, we're not building it in the UK because there isn't the incentive for it. The same with storage, we'll build it if there's a service to provide and money to be made.*

Source: authors.

Table 29 The socio-cultural challenges of hydrogen (n = 111)

Theme	Rank	Frequency by interview		Participant code	Representative quote
Public and private lack of trust in project development and implementation	1	20	18.01%	R16	*People are mistrustful of the oil and gas industry. So, because this blue hydrogen involves taking natural gas to produce hydrogen, they can, therefore, potentially be sceptical because of the oil and gas industry's role in trying to make fracking happen. They can come from the point of, "I don't trust you because of my past experience with fracking."*
Local opposition	2	13	11.71%	R57	*We have seen some local opposition groups, with some of the other clusters, appear recently. That's been quite eye-opening but, also, not surprising, given the angle which they're approaching things from and maybe some of the miscommunication and misinformation which is being spread around. I think, for us, we're confident what we're doing is the right thing. Any response to a backlash would be highly informative, factual, and almost treated as an educational exercise more than anything*
Boilers replacement	3	12	10.81%	R52	*I think you're aware that the other bigger piece to this is whether the national gas network is converted to take hydrogen in addition to gas and to put, maybe, as much as 20% hydrogen into the network, which, of course, will need some modifications to people's heating, and boilers, and so on and so forth.*
Insufficient workforce	3	12	10.81%	R19	*We've got all of these major infrastructure projects all going on almost at the same time. That's where we're likely to hit a constraint: having enough construction workforce to build it all.*
Lack of trained workforce	4	10	9.09%	R23	*Further up the scale you've then got the person who is maintaining the bus, with a hydrogen engine, again, that's a different skill level. How do you deal with hydrogen fuel cells? How do you then design the systems to manufacture and maintain, repair, replace, recycle; all of that as well. So, some of it is existing, some of it are things that haven't, I guess, aren't in place yet.*

Source: authors.

Table 30 The political challenges of hydrogen (n = 111)

Theme	Rank	Frequency by interview		Participant code	Representative quote
Tension and competition among stakeholders	1	30	27.02%	R108	*Yes, there is much more competition among most stakeholders. There are two major blue hydrogen projects, us and BP who has a major blue hydrogen project in the region. We are competing for customers, essentially. But we are also competing for BEIS funding through the cluster-sequencing process as well. And there are numerous green hydrogen projects. BP also has a green hydrogen project in the region, EDF Renewables and Protium have green hydrogen projects, too. Naturally, there would be tension for who gets the most customers and funding.*
Bureaucracy and lack of political action	2	29	26.12%	R45	*There are loads of elements to it. There's the coordination between BEIS and Treasury and bearing in mind that everything fell apart in the last CCS project – the last competition, essentially – because BEIS and Treasury, seemingly, were not coordinated when it came to the end of the process. I think that was a big part of what happened; the money, essentially, had to be allocated elsewhere, and the project came apart. They're certainly bringing Treasury more with them this time, but there are huge problems – well, huge difficulties, let's say – in trying to create an industry that's this big at this pace.*
Inconsistent policy strategies and changes in government	3	24	21.62%	R45	*There are conflicting policies and regulations, which doesn't always help. You've got, take for example, regulation around planning that actually contradicts what the net*

Table 30 (*continued*)

Theme	Rank	Frequency by interview		Participant code	Representative quote
					carbon zero policy is on a national basis. You also have policies that cover the same subjects but are covered by two different departments. You've got, again, going back to the hydrogen mobility one, hydrogen as a fuel source is covered by the Department for Business, Energy, and Industrial Strategy but hydrogen use as a fuel source on the roads is covered by the Department for Transport. The two of them aren't working collaboratively together, that has an influence on legislation and project development.
Insufficient government support	3	24	21.62%	R21	*You know, the 5 GW target, that's not been matched by the caps that have been put in associated with the hydrogen business model. They're talking about 5 GW, that's what the government is trumpeting, but they've only actually committed funding for 1.5 GW so far (Laughter) by 2027. I don't suddenly see them, unless they get their act together, allocating sufficient funding for another 3.5 GW of hydrogen from 2027 to 2030. That perhaps curtails our ambition, our ability to deliver, a little bit because we want to deliver, ideally, I think 3.5 GW/4 GW of hydrogen ourselves by 2030. If the funding isn't there or the mechanism isn't in place, the competitions aren't in place to enable us to do that*
Lack of a regulatory framework	4	23	20.72%	R75	*I think the lack of coherent regulation. Because hydrogen cuts across gas regulation but also electricity and auto regulation, and those three areas operate in silos, it makes it quite difficult to navigate the way. Then in that same vein, the deployment of the projects and the different permissions, and permits, and this and that that are needed, again they're in those three separate areas, which don't really talk to each other that well.*
Geographic tensions	5	20	18.01%	R78	*The Acorn project wasn't awarded funding because it was in Scotland, why should the UK government give Scotland money when it could be independent soon, or they're just trying to get at us?*
The scale and magnitude of the project	6	18	16.21%	R69	*I think that for a lot of people, ultimately, we want to use hydrogen as a fuel because that is the ultimate zero-carbon fuel. But then developing that hydrogen economy within the UK is also complicated. Building that production of hydrogen around the country. And it has to be green hydrogen as well. How are we going to scale up to produce that amount for industry as well as for injecting it into the gas grid? Is there going to be enough? Are we producing our own? Where are we going to put it? Are we going to take from a supplier? Where is the supplier? Where are the pipelines going to be? In the UK that is a very complicated question as well.*
Policy investments	7	17	15.31%	R101	*The biggest challenge is changing government policy, and government policy that pushes people in the wrong direction, subsidizing fossil fuels instead of renewables, for instance. Or just all sorts of things that governments can randomly do which can make a project not really feasible or send the wrong message.*
National and international instability	7	17	15.31%	R48	*If final investment decisions are needed from the government, and if there is no stability in the government to make those decisions, those decisions could keep getting pushed back and back until there is someone there to make the decision effectively. Things, of course, get more complicated if there are international conflicts such as what we are just living with the Russia-Ukraine war and the increase in the gas prices.*
Lack of policies for hydrogen storage	8	16	14.41%	R39	*We sit on the hydrogen expert group that BEIS is running, and we meet with them bilaterally. Like I say, I think we want to see some sort of business model for storage. we think there needs to be some sort of intervention. There are multiple options that could work, there could be a regulated model, a market-based model, something similar to a cap and a floor model. I think there are options, but we've not identified what we think is the best solution. There's probably some work for the government and industry to do in that space.*
Project ungovernability	9	15	13.51%	R38	*In terms of hydrogen power, the hydrogen strategy sets out that there's a role for hydrogen in the power sector but there's very limited detail or progress on what those policy frameworks or business models might be. Without clear guidelines on this, it is very difficult to have control over such a big project. We'd say that, realistically, you would need some sort of government intervention as the market alone isn't going to deliver that sort of investment.*
Delays in delivering	9	15	13.51%	R21	*The biggest challenge is making sure all of these things, consents and business models, come together at the same time. For instance, if I had to bet my house on it, I'd say, "No, we won't be ready by 2025. It'll be 2026 or something." That's because, just, something won't go as planned. Probably, government won't get its act together in terms of getting the business models in place in time.*

Source: authors.

Table 31 The environmental challenges of hydrogen (n = 111)

Theme	Rank	Frequency by interview		Participant code	Representative quote
Prioritizing blue over green hydrogen	1	48	43.24%	R101	*it is the [hydrogen] policy. It's like they say they're colour agnostic, but it's quite clear that the policy prioritizes blue because it is easier to scale up quickly. Then we'll transition into green, but I just didn't see how such an easy transition would happen, for one. Yes, it seems like they're not being agnostic to the colour, really, at all.*
Allows oil and gas companies to keep burning fossil fuels	2	25	22.52%	R16	*I suspect that the oil industry knows that it can, it can continue to explore and probably get permission to extract oil from places like the North Sea for another five or 10 years. They will continue to make profits burning the same fuels for longer.*
Emissions will still be generated	3	20	18.01%	R34	*Not to complicate things too much but about 20% of our emissions are process emissions. We melt carbonates so, even if the fuel that we use is 100% renewable, the fact that we are melting carbonates, and that process emits carbon itself, means that we'd still have 20% of our emissions to deal with.*
Contamination by residual gas	4	6	5.04%	R61	*If you want 100% hydrogen, and HyNet is about providing not blended hydrogen natural gas but 100% hydrogen to customers, then you don't want contamination with natural gas. If you're going to put it to fuel cells and things like that then you definitely don't want contamination with natural gas.*

Source: authors.

Table 32 The technical challenges of hydrogen (n = 111)

Theme	Rank	Frequency by interview		Participant code	Representative quote
Infrastructural challenges	1	37	33.33%	R19	*There are a number of other studies going on right now, you may have seen in the news, around 100% hydrogen in homes as well. That's interesting. It's a lot harder because you have to do the conversion of the equipment. Fundamentally, moving an entire village to hydrogen is quite a big undertaking.*
Transport, storage and leakage	2	36	32.43%	R5	*So, also there are big plans to build hydrogen infrastructures around Merseyside, Liverpool, Manchester, which would then also be heating homes, powering industries and maybe even cars. This is all highly speculative, but in my view, you cannot just do the hydrogen through normal gas pipes, because the molecules are smaller than natural gas, and you need to build entirely new pipes. It's uncertain if it will work in homes, because the whole heating system needs to changed, but you can see these fantastic plans with nice pictures and grass, with all these pipelines and infrastructures and windmills, and hydrogen storage, and fantastic promises, of course, about it how, if you invest this much money, it's going to create 300 000 jobs*
Ensuring supply security and renewables availability	3	34	30.63%	R25	*There are very different considerations around it from the intermittency of electrolytic hydrogen, expecting that the green hydrogen is going to be produced from renewable sources, which have more intermittency issues with them over a natural gas supply. So, there are intermittency issues that need to be considered with the green hydrogen business models and how the low carbon hydrogen standard comes in.*
Safety risks	4	25	22.52%	R70	*I'm not just talking about the offshore element. Hydrogen onshore, like we have with natural gas as well, we've got safety issues there. The Japanese have had a hydrogen programme for decades and even within laboratories they've had a number of fatal incidents and so on. It's different, hydrogen is different. I think we need to understand it better. Safe hydrogen systems can be developed, and safe ammonia systems can be developed, but we need to look at it. We need to look at it carefully.*
Technological challenges and low TRL	5	22	19.81%	R100	*If you look at green, we also have problems in Europe with green electrons, taking green electrons to turn them into hydrogen. That isn't, optically, always the right thing to do either, especially when there's still brown lignite generated electrons in the market. So, I think green is going to come but it's going to come at a pace to be defined. Only when the technology is fully ready.*
Fuel switching	6	14	12.61%	R28	*We have a project in our TBM mill looking at switching hydrogen, green hydrogen for our CH4. It's not as simple as just switching hydrogen for CH4, it's a different mass and so therefore it's a different heat transport with the burners. The burners have to be changed. The dynamics of the reheat furnaces have to be changed, it's not just a switch one out switches one in.*
Lack of evidence the technology works	7	13	11.71%	R32	*As you say, the Gigastack, the Allam Cycle projects which are different to what I guess you'd potentially say the traditional CCS idea is. Ultimately, yes, all of them are new and have not really been proven at scale before and definitely not in the UK*
Different caloric values	8	10	9%	R16	*[Hydrogen pipelines] There are differences in the calorific value of the gas, which means that you need more hydrogen to have the same effect that you get with natural gas. We are replacing our old pipes that need replacing with plastic ones to help make the network hydrogen ready. So, there are challenges that various different programmes of work are looking at overcoming.*
Inefficient energy use	9	9	8.10%	R5	*I would say, instead of carbon capture and blue hydrogen, do blue hydrogen if you need to do hydrogen, but do as little hydrogen as you have to. We might need to have some,*

Table 32 (*continued*)

Theme	Rank	Frequency	by interview	Participant code	Representative quote
					you know, to fly airplanes or whatever, but as little as possible, because it's an inefficient way to use energy. You lose a lot of the energy between your written source and burning the hydrogen. So, it's not an efficient way. It would be more efficient to produce electricity directly from renewables, and then use that electricity directly to run whatever it is that you need to run, or heat, or whatever the issue is
Lack of reliability	10	8	7.20%	R6	*So, if you're putting in hundreds of millions of pounds' worth of hydrogen, you need to be fairly confident that it's not just going to evaporate through the rock and you've just wasted, sort of, half a billion pounds worth of hydrogen into the sea. So, you need to have it fairly well-proven evidence that the technology will work*
Embrittlement	11	4	3.60%	R62	*it's obviously more complicated because with pure hydrogen there's a risk of embrittlement to the metal pipes. There's a risk of even embrittlement to some of the sealing materials as well: permeation.*
Flexibility	12	1	0.9%	R11	*Flexibility is an issue, and it's a big issue. When the power price is getting pushed, we need to be flexible. We need to come off because the power prices are being pushed down by all of the wind coming in. So, when the wind's blowing and all the wind farms are generating high, it's pressuring power price down and sending the right signal, then an emitter like us should turn off, allow that on and then come back up. That doesn't work for the hydrogen producer.*

Source: authors.

Table 33 The economic challenges of CCUS (n = 111)

Theme	Rank	Frequency	by interview	Participant code	Representative quote
The high costs of CCUS deployment	1	41	36.93%	R38	*It is too expensive. I think that's a danger with the CCS approach, is that the government has got to be prepared to actually say, "It's going to cost a lot initially, but we'll recoup that in the long term once you've got a viable model." How we actually charge and what that economic model should be.*
Inappropriate business models	2	28	25.22%	R93	*It is not a product. It is really an entirely new business model. You are being asked to take effluent waste away and store it forever. Even though the UK Government, I guess, after 20 years will take on the liability. How to really make that palatable. Because even if you say, "By 2050 it has got to get there," it is still not – if it was by 2027 it had to be net zero it might be a different story. Maybe you can just unpack a bit for me how that business model works. And then how is it even a business model? Because it doesn't make much business sense, apart from they are going to shut you down by a certain date in 25 years.*
Uncertain profitability	2	28	25.22%	R54	*The risks that we see are a risk in investing in an area and then not being able to sell your product. That's a huge risk because the market has not yet been created for what we are trying to make and sell. So right now, you have a lot of companies that are showing real leadership and a healthy sense of risk because they're investing in a project where there's no guarantee they can sell the end product in the UK. Because while the government has made very positive advances in creating a market for these products, it's not finished. I've been working on some of these frameworks for over ten years, and it's still not final. So, that is a huge investment risk for companies that are trying to work in these clusters.*
Lack of carbon price	3	23	20.72%	R28	*At the moment, we are worried about the price of carbon. This gives you some certainty there on where you're going with the price of carbon and it gives you a mechanism of decarbonising, which does have some financial impact, but not as great as it would be if we had to go out and do carbon capture without any Capex help, without any Opex help. It gives us a route to decarbonisation, which we have to do, which is partially funded.*
A lack of market for GHG removals	4	16	14.41%	R45	*There is no clear market for greenhouse gas removals credits, which is at moment, one of our biggest concerns at DRAX.*
High subsidies	5	11	9.90%	R55	*The high subsidies delivered to CCUS entails the risk of diverting resources away from renewable energy, with implications of slowing down a cleaner energy transition. These high subsidies are creating a dependence on CCUS without really addressing the root of the problem: burning fossil fuels.*
Stranded assets	6	9	8.10%	R38	*It's just that whole model. If you are putting carbon underground and you can't use it, certainly a large part of it you probably won't ever be able to use, it will just be storage, there is no value in storage in that sense because you are not going to do anything with it. It's going to be interesting how that element of unusable carbon that you are just storing, how you actually make that financially viable for a company. Who owns those storage? Should it be the oil company? Should it be the UK PLC that owns those storage? Yes, there are still a lot of questions I think in terms of how that works and how you have a financial model that works for businesses.*

Source: authors.

Table 34 The socio-cultural challenges of CCUS (n = 111)

Theme	Rank	Frequency by interview		Participant code	Representative quote
Public and private lack of trust in project development and implementation	1	28	25.52%	R2	*There are a lot of battle scars from the fracking industry, if there is any association between the CCS side of it and fracking, there will be very difficult conversations to be had, some trust was lost during the fracking debacle. So, in terms of public perceptions, this is really important.*
Local opposition	2	13	11.71%	R94	*The public is definitely concerned. Local public opposition has cancelled projects before; we are not exempt from that. The famous European project Barendrecht, in the Netherlands, was a project that was stopped because of local opposition. Here something similar could happen.*
Lack of trained workforce	2	13	11.71%	R27	*One of the things that we didn't really touch on, but it is a challenge for the sector, is skills in the sense of the trained-up people and what is the future need of the skills and attracting the right skills. That is always going to be a challenge for the sector. Because it's so new, I don't know if there is quite the training available or the availability of skills, just yet, to deliver the outputs that we need.*
Insufficient workforce	3	7	6.30%	R66	*I think the major risk for us, I think the biggest risk, is that we can't get the people to do the work. And that's possibly a risk for a lot of different organisations, at the moment, in that the workforce is really diminished, since we left the EU, and that means that it's just not so easy to find skilled workers.*

Source: authors.

Table 35 The political challenges of CCUS (n = 111)

Theme	Rank	Frequency by interview		Participant code	Representative quote
Unaligned tasks among stakeholders and poor communications	1	26	23.42%	R13	*There are lots of conversations going on with businesses, academics and government. Sometimes, I haven't yet got a handle on whether there are other stakeholders involved, like community side, social side interactions. There's a lot going on and many people are involved, sometimes you may be lost among so much going on. I mean you mentioned ETI getting cancelled and CCS, this is like the third time, right? It was going ahead, it was cancelled, it was going ahead, it was cancelled. Shell gas was on and then it was off. UK energy policy just seems kind of a quagmire. I bet that no one really knows what exactly is going on.*
Insufficient government support	1	26	23.42%	R3	*The second thing is obviously the government's appetite to support this financially, so these things do not make money, they require some kind of business model support, subsidy regime in the same way as other new green technologies have. And government I don't think will want to just do it all at once if that makes sense. So, there would be some kind of financial limit imposed by government in terms of how many projects they might support in any one phase.*
Competition (*i.e.* over funding and capacity)	2	25	22.52%	R88	*In a couple of Innovate UK workshops, one of the challenges we've put up is trying to encourage more cross-cluster collaboration. Unfortunately, at the moment, the way that BEIS have set it up, we're actually in competition with each other.*
Bureaucracy and lack of political action	3	24	21.62%	R50	*My personal view is, I think, BEIS is very enthusiastic and would like to support these projects, but the sticking point will be with Treasury, not with BEIS. So, it depends very much on how negotiations between BEIS and Treasury go. That, I think, was also the problem in the past.*
Geographic governance	4	21	18.91%	R4	*I think one of the challenges that the Humber cluster faces, compared to the Teesside cluster, is that the Teesside cluster falls under one local government authority, whereas the Humber cluster, being so massive, is covered by four, I think, which makes it quite difficult*
National and international instability	5	20	18.01%	R47	*There's political instability. Obviously, there is geopolitical instability. These governments in this country typically are meant to be in place for five years, but we're going through a period just now where there have been significant changes on the national government, the Ukraine crises and the increase in gas prices. All these elements could endanger the deployment of this megaproject.*
The scale and magnitude of the project	6	16	14.41%	R86	*I feel like there's not the skill or capacity – particularly if the project is being done for public benefit, there's not the skill and capacity in governments to be able to manage that kind of thing well. I have to remain optimistic because we need to get there but yes.*
Lack of a regulatory framework	7	15	13.51%	R37	*So currently, the planning regulations are an interesting one. So, carbon dioxide pipelines are not covered in national planning statements at the moment, which would be really helpful for us in getting planning for all the assets. So, we continue to lobby for MPS around CO_2 which are due, but I think slightly delayed. So that is an interesting one clearly that is the Health and Safety Regulation as well around it. But there isn't a safety case that has been granted yet, for anybody, in the UK for that sort of transportation. So that is another regulatory environment that we need to bring along, but the big one is the business models, ensuring that government*

Table 35 (*continued*)

Theme	Rank	Frequency by interview		Participant code	Representative quote
					have the necessary primary and secondary legislation that they need in order to be able to grant them
Inconsistent policy strategy and changes in government	8	14	12.91%	R29	*Right now, very inconsistent. The UK is probably the furthest advanced in the world at working through its entire regulatory system to make low-carbon stuff happen, and it's a mess. We've had 100 years of legislation being devised where energy was just assumed to be available and carbon emissions and climate change just wasn't a thing. Unconsciously, emissions are built into everything and it is a massive exercise to change the policies in these areas. That's why you've got what at the moment, I think, is quite a fragmented approach to carbon capture and to decarbonisation more generally. There are initiatives to support wind, there are initiatives to support hydrogen production, there are initiatives to support solar, there're just about initiatives to support CCS but they're all... They've been developed in isolation, they're not joined up.*
Lack of cooperation among stakeholders	9	4	3.60%	R41	*There was actually an emphasis on knowledge not being shared between our individual projects within different clusters. If anything, we were trying not to share among our own projects.*

Source: authors.

Table 36 The environmental challenges of CCUS (n = 111)

Theme	Rank	Frequency by interview		Participant code	Representative quote
Allows oil and gas companies to keep burning fossil fuels	1	27	24.32%	R5	*For carbon capture, get rid of the carbon in the first place, don't capture it. Don't make it and don't produce it. That should take priority. So, that would be if somebody responsible for this asked me, with genuine interest, what do I think, that's what I would answer.*
Other environmental impacts could emerge (*i.e.* construction of plants and transporting biomass for BECCS)	2	25	22.52%	R11	*With biomass, you're still emitting the same amount of CO_2, if not more. Okay, you're planting trees to cover that. There's another question about, okay, the transportation, the impact of the transportation as well when you're bringing it from North America instead of growing it locally, which might have been the concept originally, but to get the scale, the concept is one balances off the other, I don't think it does.*
Emissions will still be generated	3	24	21.62%	R84	*I think, if you're looking at the other emissions like SO_x and NO_x, normally they don't change through the CCS application. What changes is that, because you're using an amine that you regenerate, the amine creates a new emission. Again, that is one of the discussions that we're having with the A to Z on what those emissions are, how harmful they are. To some extent, you're replacing one emission with the other.*
Technology could fail to meet climate targets	4	18	16.21%	R63	*The risk question is one of risk of failure to meet targets springs to mind straight away. You roll out a certain approach, you roll out a certain strategy with the objective of meeting a particular emissions target. If something goes wrong in that process, if one of the pillars you were relying on doesn't deliver for some reason, then you are going to be missing that wedge of emissions that it was responsible for, whatever that technology is.*

Source: authors.

Table 37 The technical challenges of CCUS (n = 111)

Theme	Rank	Frequency by interview		Participant code	Representative quote
Infrastructural challenges (*i.e.* leakage)	1	39	35.313%	R48	*We've also had big problems with this in Indonesia and the North Sea, if the wells have not been capped and they leak, then they're going to leak whatever they're leaking. Whether they're leaking methane or whether they're leaking crude or whether they're leaking CO_2, I mean, it's all a problem, you don't want either of those, you don't want any of those in the ocean, do you?*
Physical constraints (*i.e.* capacity for storage)	2	29	26.12%	R1	*I think principally when you develop a transport and storage network, especially the ones that are looking at quantities of CO_2 they are looking to be putting millions of tonnes of CO_2 underground, you have to outline where would be your*

Table 37 (*continued*)

Theme	Rank	Frequency by interview		Participant code	Representative quote
					geological storage site where you could be storing in, and there are limits to how much you can inject at any one time.
The lack of evidence CCUS works and low TRL	3	26	23.42%	R69	*We need to work with manufacturers to produce these new plants, trial them, and ensure we are assured of how they are operating before we even install them. Make sure that they are producing the amount of product that we want. Obviously, we don't really want to install something and then go from producing a hundred to two tonnes a day. So that is a big risk. Making sure that our equipment is ready for all of that.*
The geography of the project (*i.e.* finding adequate sites for storage)	4	24	21.62%	R94	*The other thing I'll say, as well, is that in contrast to the engineers, geology has a sort of inbuilt uncertainty around it. You're never going to know exactly what the geology is exactly going to be, at a kilometre's depth, over an area of perhaps 10 × 10 km^2. You'll never know exactly what the geology is.*
Transport infrastructure	5	23	20.72%	R70	*What you're putting into your CO_2 sinks is not pure CO_2. There's a cost associated with purifying it and separating all the other stuff. The sheer volumes, the volumes at the capture level, the volumes at the transport and the volume at storage, the underground stores and so on, there's so much we don't know about it.*
Not a clear application of carbon utilisation	6	19	17.11%	R89	*If you look at the Net Zero Teesside Deployment Scheme that is definitely CCS, so it's carbon capture and storage. There is no usage in that at all.*
Carbonate	7	3	2.70%	R51	*You know that most fizzy drinks are acidic solutions; they are like acid. This new solution is also acid. It has CO_2 in it. It starts reacting with the rock around it; some chemical reactions would happen. If that chemical reaction happened, the CO_2, which is now in liquid, would be converted to a solid. We call it carbonate. What happened is that CO_2 from gas phase came to liquid and then from liquid to solid. That is going to be a permanent storage of CO_2. That CO_2, which is now a solid phase, there is no way for it to escape. We have to start investigating and looking at this problem to understand the risk, to reduce the risk or actually control the risk or the issues around the risk.*

Source: authors.

Table 38 The equity and vulnerability challenges (n = 111)

Theme	Rank	Frequency by interview		Participant number	Representative quote
Increase in energy costs and services to consumers	1	41	36.93%	R81	*Coupled with concerns on safety, I think hydrogen will push more families into fuel poverty because it will be more costly than the gas it derives from blue hydrogen with CCS. It's got to cost more than that and more than the electricity it's derived from if it's green hydrogen produced by electricity being used to electrolyse water.*
Big companies will win the most	2	38	34.23%	R51	*Ultimately, the biggest winners are the big companies and corporations working on this. There will be some losers and winners, but the economic benefits will mostly be distributed among these players.*
Uncertain future of industries and erosion of workforce	3	32	28.82%	R23	*You know, a lot of the political narrative is around masses of new low-carbon green jobs. And I think there's a risk that there's no future for the traditional workforce. There's a huge risk these people may lose their jobs.*
Users will partially pay for the infrastructure	4	27	24.32%	R14	*If it doesn't work out and, we don't go for hydrogen or CCS for whatever reason, and you have to decommission as the Oil and Gas Authority requires. Ultimately, the taxpayers will pay a portion of that. So yes, there's a public concern that taxpayers are paying for these projects.*
Outsourcing national and local workforce	5	23	20.72%	R13	*Suppose it becomes a situation where delivery is outsourced, and you bring in your highly skilled engineers from Spain, North America or whatever to deliver the project because the capacity and capability aren't available in the UK. In that case, a big chunk of that economic benefit will flow out of the region.*
Lobbying from oil and gas keeps these industries alive	6	22	19.81%	R65	*One of the main drivers is that incumbents are looking for a new business related to their existing businesses and skills. That is the attraction of hydrogen and CCS, and where a lot of the lobbying – and there is quite a lot of lobbying going on at the moment, on behalf of it – comes from because it enables people to do similar things to that they did before, and carry on. So, incumbency is critical. I think, for hydrogen and CCS, you're not necessarily going to see an awful lot of new actors coming in. It's old actors doing new things.*
Promotes environmental injustices	7	20	18.01%	R65	*The employment at the plant is not touching the local communities because people who work at the plant they're doing relatively high-skilled, high-paid jobs. So, they're going to live in a nice neighbourhood somewhere else and basically do the DIDO – drive in, drive out – approach to work. It doesn't touch the local community. When we visited there, that was a big theme about trying to raise the aspirations of people, of kids at schools, who worked locally, to raise their aspirations about the kind of employment they might have. So, it's hard to say that some of these plant – this is the classic*

Table 38 (*continued*)

Theme	Rank	Frequency by interview		Participant number	Representative quote
					environmental justice thing from the US that local communities, more deprived communities – and in the US, obviously, communities with people with people of colour – can be more negatively affected there, as well. There's an analogous issue, I think, for a cluster like Grangemouth, in Scotland.
Perpetuates oil and gas companies' business model	7	20	18.01%	R55	*The fossil fuel industry is trying to reinvent itself, trying to find applications to keep itself alive, and blue hydrogen is one, carbon capture, in general, is another, and direct air capture is a third. So these are all scams, greenwashing schemes, to keep the fossil fuel industry alive. And they're supported by researchers funded by fossil fuels, mostly. And there's no reason for any of them.*
Unemployment affects local communities	8	13	11.71%	R53	*Because the big players they have high-tech jobs, they have highly professional jobs, they have highly skilled jobs. And if the local population doesn't – it might be perceived that these people are just coming in. They advertise for a highly paid, skilled, professional job, and other people, incomers, come in. So that might be seen as a loss to the benefit of the population. Somebody else is benefitting. "We're having this industry activity and the locals aren't benefitting from it."*
Unequal expenditure to decarbonisation	9	12	10.81%	R17	*They're investing trivial sums of money compared to what they spend on exploration. In exploration, that's where the real investing is. Mitigating emissions doesn't seem to be a priority compared to what they are spending on traditional business models and burning fuels.*
Requires users to make new investments	10	11	9.90%	R50	*You've got a wider issue, which is the backlash of society. I've got a house, I've got a gas boiler. The government has said that, from 2026 I think, you can't build new houses with gas boilers in, you've got to have an alternative. Sometime, not long after that, they're going to ban gas boilers so I will have to find a different way of heating my house. At the moment the technologies are air or ground source heat pumps, expensive, or hydrogen maybe will come in, but that's going to be more expensive than gas.*
Creates unequal income	11	8	7.20%	R38	*We also had to recognise that, because the pay within the offshore industry is significantly more than the general within the local economy, there is a danger that, actually, these jobs would actually start to hollow out other bits of the economy. So you would lose skill, other businesses will lose their most skilled, experienced staff, because they would be able to get jobs within Siemens, and therefore they'd lose the job. So how do we backfill that part of it?*
State protectionism to oil and gas companies	12	5	4.50%	R17	*I could see the price of renewables dropping so fast that energy CCS just becomes has to be protected quite vociferously by individual states. And you've seen this in Australia where CCS has comprehensively missed the boat for energy because the price of wind and solar in Australia has dropped so precipitously.*
Offshores emissions	13	4	3.60%	R34	*If you make it too expensive you just go somewhere else. That doesn't save the planet. It doesn't reduce planetary emissions, it just offshores them. Making steel in China is more carbon intensive than making steel in the UK because you've got to ship it here and they're burning coal to produce their electricity whereas we're not. We shouldn't offshore manufacturing, we should keep our steel plants, we should keep our fertiliser plants and our chemical plants. You have to socialise that cost, only government can do that, because companies like Essar and INEOS will just go somewhere else.*
Lack of diversity in the workforce	14	2	1.80%	R18	*So EDI [Equality, diversity and inclusion] is a huge issue in industry. Notwithstanding the fact that skills and skills gap is a huge issue, but the fact that those skills and the gap they are in is mainly oriented, particularly, to white men is one of the other challenges of the industry.*

Source: authors.

• What are the specific implementation and deployment plans, including the role of learning and experimentation?

• What are the technical skills and capabilities needed for this megaproject?

• What will it cost (whether capital expenditures, operational expenditures, or total cost)?

Policy, governance and management. • How does the megaprojects sit within the wider policy and regulatory landscape?

• Considering other megaprojects in the UK, what's your level of confidence in this one?

• How consistent are the support policies for megaprojects within the UK?

• How is such a project managed in practice, how are systems being integrated (or not)?

Benefits and risks. • What are the possible benefits to the megaproject?

• What are the technical and commercial risks, including different types of risks (environmental, financial, political, social, *etc.*)?

• Do you have any backup or contingency plans to address risks or uncertainties?

• What do you envision as the most significant challenges to implementation?

Business strategy, incumbency and disruption. • What is the overall business strategy or vision behind the project, what does involvement mean for the future of the industry?

• To what degree is the project/technology disruptive or transformative?

• What is the role of smaller companies in the project, how balanced it is between large incumbents and small new entrants? What innovative technologies are they coming up with? Will you license or seek to buy out smaller firms?

• What is the competitive advantage for doing this project within the UK?

Equity, vulnerability and just transitions. • Who stands to "win" the most from the project, and who stands to "lose?"

• What possible inequitable community impacts could emerge?

• What impact will the project have on vulnerable groups

• If social backlash occurs, do you have a plan for addressing it?

Last question (snowballing). Is there anyone else you recommend we contact for an interview? We are not only looking for recommendations, but actively seeking for missing contacts! So please could you share important contacts with us or introduce by email? Any other relevant stakeholders/companies *etc.* that you think we should talk to will help make our research stronger.

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