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# A comprehensive framework for feasibility of CCUS deployment

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# A comprehensive framework for feasibility of CCUS deployment: A meta-review of literature on factors impacting CCUS deployment

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ABSTRACT

Carbon capture, utilisation and storage (CCUS) has gained prominence as one of a suite of technologies needed for mitigating the urgent threat posed by climate change. Despite the significance of CCUS technologies to a multitude of climate mitigation scenarios, research has identified a series of challenges to deployment, ranging from cost overruns and technical failures to public opposition. Research has widely documented the range of techno-economic challenges impacting the feasibility of individual technologies. However, a growing body of research calls for the feasibility of CCUS to be assessed more holistically, with greater focus on systemic, societal and other non-technical issues. Through a meta-review of 22 recent multidisciplinary review papers on CCUS, we identify and explore a comprehensive set of challenges impacting CCUS deployment. The results show a continued focus on the techno-economic dimensions within literature. However, the meta-review also unfolds a series of issues receiving less attention in literature, from organisational and environmental challenges to issues of legitimacy. Overall, this paper contributes to a broader understanding of the critical challenges facing CCUS projects in the coming decade and provides a framework for a more holistic assessment of climate mitigation technologies such as CCUS.

## 1. Introduction

Carbon capture, utilisation and storage (CCUS) has gained prominence in climate change mitigation policy as a solution for reducing emissions from industry and fossil-based energy production to help limit global warming to 1.5 °C (IPCC, 2022). The IEA (2021) now estimate that by 2030, globally installed capture capacity within heavy industries needs to reach 375 megatons (Mt) of $CO_2$ per year, yet over the past 10 years the number of active or in-development projects has stalled (Global CCS Institute, 2016; 2020), with the majority of the 40 Mt of presently installed capture capacity limited to enhanced oil recovery (EOR) applications (Global CCS Institute, 2019; IEA, 2021). Governments, researchers and intergovernmental organisations have therefore called for a rapid acceleration in the scale-up and deployment of CCUS (Lipponen et al., 2017; IEA, 2020). However, CCUS projects display a chequered history, with numerous high-profile technical failures and a legacy of public opposition and cost over-runs constraining deployment (Sara et al., 2015; Bui et al., 2018). As such, an increasing body of work has sought to document and address the various challenges impacting CCUS feasibility to help accelerate deployment of the technologies.

To avoid or reduce project failures, research has applied a series of frameworks for assessing CCUS projects. These frameworks typically evaluate feasibility with a varying scope, ranging from a "narrow" techno-economic or business feasibility lense, to those evaluating a broader range of aspects. In line with Majone (1975) and Hvelplund and Lund (1998), feasibility is in this paper defined as a measure for how well something performs against a set of relevant constraints. Techno-economic analyses (TEA) is likely amongst the most widespread frameworks for evaluating feasibility of CCUS projects, and it provides a quantitative framework for assessing the technical and economic challenges of different processes, products or services (Zimmerman et al., 2020). TEA has therefore been extensively used to improve the feasibility of CCUS, resulting in efficiencies in the processes surrounding the capture, utilisation and storage of $CO_2$ under different settings (Throneman and Pizzol, 2019; Gladis et al., 2019; Mikhelkis and Govindarajan, 2020; Kamkeng et al., 2021; Nezam et al., 2021). However, TEAs have proven insufficient at identifying environmental challenges to CCS deployment (Viebahn and Chappin, 2021), with results often limited to

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technical conceptualisations of the environment focussed on life-cycle emissions (e.g., Fasihi et al., 2019). Furthermore, as argued by Bui et al. (2018), the decades of experience accumulated internationally makes is clear that *"it is not a lack of technical expertise that is inhibiting the commercial deployment*" (p. 1063). In a similar vein, Forster et al. (2020) criticise the narrow lens through which climate engineering technologies are typically assessed, describing a prevailing "*focus on relatively narrow techno-economic"* assessments. In a UK context, Markusson et al. (2020) argue that the techno-economic framing around greenhouse gas removal needs to be challenged and supplemented with humanities and social science amongst others to prepare for a wider range of futures. Forster et al. (2020) further warns that if the prevalence of TEA literature continues to influence the responses and opinions of expert stakeholders, as their analysis shows, then there remains a risk that important, and as yet underexplored and underreported, deployment challenges may be left out of decision-making arenas in a reinforcing loop.

Other frameworks for assessing CCUS technologies have proven useful in highlighting the breadth of challenges at the project scale. In particular, the application of the risk-management assessment framework PESTEL (e.g., political, economic, social, technological, environmental and legal; Johnson et al., 2008) to CCS projects highlight a more comprehensive set of challenges spanning multiple domains (Fozer et al., 2017; Romansheva and Ilinova, 2019). However, the PESTEL framework is commonly used for the strategic analysis of business objectives, meaning that project challenges are often described more generally whilst being viewed as obstacles which simply need to be overcome (Johnson et al., 2008). This has led to criticism being levelled as its application to complex technologies like CCS (Pikhola et al., 2017).

As a response to the shortcomings of frameworks such as TEA and PESTEL, Pikhola et al. (2017) suggests applying a socio-technical systems (STS) approach to assessments of CCUS feasibility, emphasising its value in integrating otherwise unidentified sustainability challenges. Several authors have employed such an approach in technology assessments. Markusson et al. (2012) applied STS theory in their analysis of CCS innovation, emphasising the central role of actors, organisations and governance in ensuring effective systems integration at the societal level, while Christiansen and Carton (2021) and Themann and Brunnengräber (2021) applied STS theory to highlight how actors influence the 'trajectories' of technologies such as CCS.

As seen from the literature, the scope of factors shown to impact the feasibility of CCUS projects are diverse, ranging from technology-specific techno-economic challenges to barriers embedded in the construct of organisations, institutions and societies. Yet, the large number of review papers discussing such challenges vary in scope and are often limited to either single technologies (e.g., Sara et al., 2015; Onyebuchi et al., 2018) or single geographies (e.g., Akerboom et al., 2021). Furthermore, given that research has called for greater consideration of both systemic and non-technical challenges in assessments of CCUS feasibility, there are presently few studies which document, contextualise and unfold such challenges in a systematic way. For example, Viebahn and Chappin's (2021) extensive bibliometric analysis of CCS deployment challenges identified key research "clusters" and underrepresented themes, yet the size of the analysis (6231 papers) precluded a deeper contextualisation or unfolding of the challenges identified. Furthermore, while Markusson et al. (2012) study is valuable in that it underscores the inherent co-evolution of technology and society, the carbon capture landscape has experienced a fundamental shift in the decade since its publication, with ample new lessons to draw upon as well as an increased interest around CCU (Martin-Roberts et al., 2021; Lamberts-Van Assche and Compernolle, 2022).

Thus, the objective of this article is twofold: to synthesise existing review literature in order to identify the range of challenges shown to impact CCUS deployment based on current knowledge, and to unfold those challenges typically underrepresented in CCUS feasibility research, thereby contextualising important future research agendas. This is performed via a metareview of recent review papers, with the ultimate aim of assisting researchers and practitioners tasked with deploying CCUS technologies whilst informing societal debates around how best to ensure a responsible development across society. In other words, the paper's contribution is in part to synthesise the vast amount of literature on the topic and in part to provide a grounded overview of the broad range of aspects of the feasibility of CCUS. The latter is complementing contributions by Markusson et al. (2012) and Forster et al. (2020), amongst others. As such, this article is guided by the following research question:

A What are the variety of challenges impacting the feasibility of CCUS projects worldwide?

The article is structured as follows: Section 2 presents the methodology used for the meta-review for identifying CCUS deployment challenges. This is followed in Section 3 by the main results of the analysis, focusing on the overarching deployment challenges grouped in representative categories. Next, Section 4 unfolds the results by contextualising and discussing the underexplored and underrepresented challenges against the existing CCUS research base, drawing attention to their significance with respect to deployment. Section 5 concludes with the studies main finding and a series of recommendations for future research agendas.

## 2. Methodology

The methodology section describes the main review process used in the paper.

### 2.1. Aggregation of challenges impacting ccus deployment

The aggregation of challenges impacting CCUS projects involved documentation and categorisation of the range of issues shown to impact the deployment of the technologies worldwide. This was completed by analysing recent review papers spanning multiple disciplines and technologies to develop a framework of factors known to impact feasibility. The framework was developed based on the concept of a meta-review (e.g., Cullen and Turnbull, 2005), with the high number of recent review papers providing detailed syntheses of different technologies, key themes as well as associated challenges. The framework of factors impacting deployment was revised in an iterative manner as each review paper was assessed, as outlined by the exploratory grounded-theory approach described by Strauss and Corbin (1998) and Järvinen and Mik-Meyer (2017).

The review papers analysed were identified in a literature search described in Section 2.2. In total, 22 review papers were identified, published in the period of 2018–2021. The review papers were published in journals such as the International Journal of Greenhouse Gas Control, One Earth, Nature Climate Change, the Journal of $CO_2$ Utilisation and the Journal of Environmental Management (Table 1).

### 2.2. Literature review design

The literature review was performed in January 2022 using the Scopus database following guidelines set out in vom Brocke et al. (2009) and Snyder (2019).

First, a search query was performed for English-language papers published between 2018 and 2022. This range was selected due to a recent increase in investments planned for new commercial CCUS facilities, which the IEA (2020) note as more than doubling since 2017, indicating a sharp rise in interest around CCUS and related technologies. The search was performed using the terms "carbon capture, utilisation and storage" and "carbon capture and storage" in combination with the words "deployment", "challeng*" and "barrier". Next, papers classified as review papers were selected, with journal and article title

**Table 1**
Review papers on CCUS technologies.

| Authors | Year | Journal | Article Title |
|---|---|---|---|
| Wang et al. | 2022 | Environmental Research | Life cycle assessment of combustion-based electricity generation technologies integrated with carbon capture and storage: A review |
| Akerboom et al. | 2021 | Front. Energy Res. | Different This Time? The Prospects of CCS in the Netherlands in the 2020s |
| Ghiat and Al-Ansari. | 2021 | Journal of $CO_2$ Utilisation | A review of carbon capture and utilisation as a $CO_2$ abatement opportunity within the EWF nexus |
| Hazra Chowdhury et al. | 2021 | ChemNanoMat | Chemical Fixation of Carbon Dioxide by Heterogeneous Porous Catalysts |
| Lane et al. | 2021 | Nature Climate Change | Uncertain storage prospects create a conundrum for carbon capture and storage ambitions |
| Martin-Roberts et al. | 2021 | One Earth | Carbon capture and storage at the end of a lost decade |
| Petrovic et al. | 2021 | Microporous and Mesoporous Materials | Influence of surface modification on selective $CO_2$ adsorption: A technical review on mechanisms and methods |
| Alivand et al. | 2020 | ACS Sustainable Chemistry and Engineering | Catalytic Solvent Regeneration for Energy-Efficient $CO_2$ Capture |
| Ansaloni et al. | 2020 | International Journal of Greenhouse Gas Control | Effects of $CO_2$ on polymeric materials in the $CO_2$ transport chain: A review |
| Beck | 2020 | Clean Energy | Carbon capture and storage in the USA: The role of US innovation leadership in climate-technology commercialization |
| Cao et al. | 2020 | Energies | A review of $CO_2$ storage in view of safety and cost-effectiveness |
| Dean et al. | 2020 | International Journal of Greenhouse Gas Control | Insights and guidance for offshore $CO_2$ storage monitoring based on the QICS, ETI MMV, and STEMM-CCS projects |
| Malhotra and Schmidt | 2020 | Joule | Accelerating Low-Carbon Innovation |
| Zhao et al. | 2020 | Frontiers in Chemistry | Co-treatment of Waste from Steelmaking Processes: Steel Slag-Based Carbon Capture and Storage by Mineralization |
| Azadi et al. | 2019 | Sustainability | Opportunities for mineral carbonation in Australia's mining industry |
| Galina et al. | 2019 | Minerals Engineering | Evolution of carbon capture and storage by mineral carbonation: Data analysis and relevance of the theme |
| Woodall et al. | 2019 | Greenhouse Gases: Science and Technology | Utilization of mineral carbonation products: current state and potential |
| Bui et al. | 2018 | Energy and Environmental Science | Carbon capture and storage (CCS): The way forward |
| Haszeldine et al. | 2018 | Phil. Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences | Negative emissions technologies and carbon capture and storage to achieve the Paris Agreement commitments |
| Onyebuchi et al. | 2018 | Renewable and Sustainable Energy Reviews | A systematic review of key challenges of $CO_2$ transport via pipelines |
| Sharma | 2018 | Carbon Management | Silver bullet or bitter pill? Reassessing the scope of $CO_2$ capture and storage in India |
| Teixeira et al. | 2018 | Biofuels, Bioproducts and Biorefining | Gas fermentation of C1 feedstocks: commercialization status and future prospects |

subsequently screened to exclude papers from unrelated scientific fields or where CCUS technologies were not implied. This was followed by a review of abstracts to exclude papers where challenges or barriers, or ways of facilitating deployment, where not discussed. Unavailable articles were discarded from the results, yielding in total 22 review papers.

It should be noted, that although the 22 review papers comprises insight from a very large number of scientific papers, the number of papers analysed may be considered a limitation to the validity of the methodology, when seen in terms of the significant body of research that exists around the subject. Furthermore, the meta-review approach provides limited insight into what the investigated review papers deliberately, or accidentally, do not include in their reviews, and there is a chance that the inclusion of more review papers would add to the comprehensive framework.

### 2.3. Data collection

The identification of CCUS deployment challenges was performed using content analysis in a systematic, iterative and collaborative process (Snyder, 2019):

1 **Scoping**: The 22 review articles identified underwent initial scoping, with relevant sections of text identified from the contents list and article sub-headings e.g., “Commercialisation of CCS: what needs to happen?” (Bui et al., 2018) and “Constraints on storage developer confidence” (Lane et al., 2021). Discussion and conclusion sections were reviewed in full. Passages of text describing challenges to — or means to accelerate — deployment were subsequently documented. Next, keyword searches were performed using the terms ‘challenge’ and ‘barrier’ to widen the field of analysis and identify text missed in the first iteration.
2 **Data coding**: After relevant passages of text were flagged, keyword identifiers were applied to describe the deployment challenge using a single phrase or word. For example, a discussion of how subsidies from government may encourage investment in CCUS projects was labelled as "subsidies".
3 **Determination of groupings**: The large number of recorded keyword identifiers were synthesised into common language codings in a continuous and iterative manner. For example, phrases describing the same issue, e.g., “$CO_2$ price” and $CO_2$ pricing”, were unified under “carbon pricing”. Next, keyword identifiers were interpreted and grouped into higher-order thematically related sub-categories, or “feasibility challenges” (see the supplementary material file). Here, a phrase which accurately described the range of keyword identifiers under such a grouping was selected. This was done using an inductive approach (Given, 2008) to ensure that the coded data were contextualised based on observed linkages to other individual or groups of keyword identifiers. Codings and sub-categories were discussed between the authors and revised as new data emerged (i.e., Järvinen and Mik-Meyer, 2017).
4 **Categorisation:** Lastly, the critical deployment challenges were grouped into categories using an iterative approach involving discussion between the authors to ensure consistency and a common interpretation for the different factors. The 6 categories identified include economic, social, technological, environmental, institutional, and organisational.

The categories are to some extent interdependent and overlapping in focus, however, each of them are reflecting an important topic in literature. Institutional and organisational aspect may in particular be seen as overlapping, but whereas institutional factors are understood as elements of formalised frameworks external to CCUS projects, organisational aspects are understood as managerial aspects within CCUS project development. These categories are well in line with the aspects of feasibility mentioned in the introduction.

## 3. Results

The aggregated framework of challenges identified in the 22 review papers is presented in Table 2. The framework underscores the complexity and diversity of issues shown to impact the deployment of CCUS. For the comprehensive list of keyword identifiers and groupings behind each category, along with accompanying references, see annex A. The challenges and content of each category are unfolded in the following sections.

### 3.1. Economic feasibility challenges

Significant *costs* impact the feasibility of CCUS by slowing technology uptake, with major capital (CAPEX) expenditure needed to scale and deploy full-chain infrastructure (Martin-Roberts et al., 2021). High operational costs further inhibits deployment due to considerable energy requirements of capture, transportation and storage systems (Bui et al., 2018; Lane et al., 2021), while the feasibility of various CCU processes remain similarly constrained due to costs associated with energy and the high costs of obtaining suitable chemical feedstocks, which render certain synthesis pathways (e.g. green fuels, mineral carbonation) economically unviable (Azadi et al., 2019; Woodall et al., 2019; Akerboom et al., 2021).

Literature therefore highlights the need for *financial support* in the form of tax credits, subsidies, direct government financing or grants (Akerboom et al., 2021; Martin-Roberts et al., 2021). Financial support is seen as key to the overall feasibility of CCUS, in that it helps to overcome first-mover disadvantages (Beck, 2020) by providing reducing upfront capital requirements while mitigating financial security in the face of uncertain costs, which in turn encourages private investment (Sharma, 2018; Lane et al., 2021).

*Market drivers* also impact the economic feasibility of CCUS, with effective $CO_2$ pricing needed to ensure a penalty for emitting $CO_2$ (Cao et al., 2020), thereby driving emitters toward mitigation technologies such as CCUS (Sharma, 2018; Beck, 2020; Martin-Roberts et al., 2021). Emerging markets for $CO_2$ are also helping to drive interest in the technologies, with $CO_2$ a crucial feedstock in electrofuels such as methanol, as well as in a range of industrial chemical feedstocks (Teixeira et al., 2019; Galina et al., 2019; Akerboom et al., 2021). However, while EOR has long created a demand for fossil $CO_2$ in the United States (Martin-Roberts et al., 2021), the present global demand for $CO_2$ for a range of CCU products could easily be met by a single state-of-the-art coal-fired power plant (Bui et al., 2018). Furthermore, the current $CO_2$ price in established markets such as the EU ETS is largely seen as inadequate in preventing the release of emissions to air (Haszeldine et al., 2018; Dean et al., 2020), while investment in CCUS projects may also be disrupted in the face of unexpected global events and fluctuating markets (Ghiat and Al-Ansari, 2021).

There are a lack of commercial *business models* for CCUS, with various factors needing to be overcome to improve CCUS feasibility, including how to share and transfer financial risk, limitations in existing insurance markets, cross-chain default – where the failure of one component in the CCUS supply-chain jeopardizes operations in other parts of the chain –and uncertainty over liabilities in the event of $CO_2$ leakage (Bui et al., 2018; Beck, 2020; Akerboom et al., 2021; Martin-Roberts et al., 2021). Furthermore, new mechanisms for transferring or minimising the financial risk associated with CCUS value-chains — such as contracts for difference — are needed to help minimize investor risk in the event of fluctuating $CO_2$ streams (Bui et al., 2018), while questions regarding project financing also persist (Martin-Roberts et al., 2021).

**Table 2**
Framework of factors impacting the feasibility of CCUS technologies.

| Category | Description | Feasibility challenge |
|---|---|---|
| **Economic** | Factors impacting the economic viability of CCUS, both internal and external to the project | *Cost*<br>*Financial support*<br>*Market drivers*<br>*Business models* |
| **Social** | Factors affected by societies' trust, belief and perception of CCUS | *Public acceptance*<br>*Social licence to operate* |
| **Technological** | Factors impacting the physical, temporal and spatial implementation of CCUS technologies and systems | *Performance issues*<br>*Geological*<br>*Proximity to infrastructure*<br>*Innovation* |
| **Environmental** | Factors which threaten the environmental value of CCUS technologies and systems | *Environmental impacts*<br>*Mitigation potential* |
| **Institutional** | Factors describing the political environment and legal infrastructure of a country | *Policy*<br>*Legislation*<br>*Regulation*<br>*Political support* |
| **Organisational** | Factors related to how CCUS initiatives are managed and organised | *Coordination and management*<br>*Hubs and clusters* |

### 3.2. Social feasibility challenges

The feasibility of CCUS can depend on the level of *public acceptance* the technologies attain, which is affected by trust in key stakeholders, negative associations between carbon capture and fossil fuel industries, perceived safety risks and the degree and form of public consultation (Sharma, 2018; Dean et al., 2020; Akerboom et al., 2021). A lack of public acceptance has proven historically to be a critical barrier to various CCS initiatives and policies, with opposition emerging particularly around onshore CCS projects (Akerboom et al., 2021), often driven by concerns over the long-term safety of $CO_2$ storage, a public reaction interpreted as a 'not in my back yard' tendency or a lack of knowledge regarding the technologies (Ansaloni et al., 2020; Martin-Roberts et al., 2021).

While public acceptance may be key for getting a project off the ground, the *social licence to operate* (SLO) is seen as crucial for its long-term success (Lane et al., 2021). In particular, the SLO, which describes the ongoing approval of a particular project within a local community or group of actors, is recognised as being important for helping build investor confidence in a particular initiative (Cao et al., 2020; Lane et al., 2021).

### 3.3. Technological feasibility challenges

Research underscores diverse *performance issues* throughout the CCUS value-chain. During the capture process, significant energy penalties may occur (Alivand et al., 2020), while solvent degradation (Bui et al., 2018), varying absorption efficiency (Ghiat and al-Ansari, 2021) and challenges caused by flue gas composition and concentration Teixeira et al., 2019) reduce the overall efficiency of the capture process. The presence of impurities and water in compressed $CO_2$ during transportation by pipeline can also result in significant pressure drops and the precipitation of hydrates, which impacts operational efficiency and may led to blockages (Bui et al., 2018; Onyebuchi et al., 2018; Ansaloni et al., 2020).

G*eological* challenges continue to pose significant barriers to the deployment of CCS. A key risk remains the uneven distribution of suitable storage reservoirs across geologic basins worldwide (Lane et al., 2021), while operational CCS projects, such as Snøhvit, have been impacted by declining injectivity due to pressure build-up in the reservoir (Bui et al., 2018). Furthermore, while various national initiatives have mapped theoretical $CO_2$ storage volumes (Akerboom et al., 2021), translating this into reliable estimates of subsurface capacity remains highly challenged due to uncertainties regarding injection rates, $CO_2$ dissolution mechanics, permeability and reservoir pressure, attributes which can only be determined via detailed site analysis (Lane et al., 2021). As such, the current rate at which geological storage sites are being identified and appraised is considered too slow and uncertainty around $CO_2$ storage capacity too high (Beck, 2020), which risks slowing the deployment of CCS.

*Access to infrastructure* represents an important entry barrier for emerging and smaller scale CCUS projects, with increasing distance between a source of industrial emissions and both storage sites and existing transport mechanisms resulting in higher costs (Beck, 2020; Martin-Roberts et al., 2021). In a similar vein, the existence of major pipeline networks in the US, which connect sources of emissions to geological storage sites, represents a major enabler for CCS, helping to minimise entry costs of $CO_2$ transportation in the value chain (Martin-Roberts et al., 2021).

Greater *innovation* is needed to facilitate the scale-up of projects, from demonstration to full-scale and technologically mature solutions. For example, the technological readiness level (TRL) differs between technologies and sector applications, with the TRL of monoethanolamine (MEA) $CO_2$ capture differing depending on which industry the technology is applied to (e.g., the power sector or cement industries differs) (Bui et al., 2018). Generally, the geological storage of $CO_2$ has been operating commercially for many years and has a high TRL (Dean et al., 2020), yet $CO_2$ storage in coal beds remains commercially immature (Cao et al., 2020). Several CCU pathways are also approaching maturity, yet wider market penetration remains slow due to cost and efficiency challenges (Bui et al., 2018; Akerboom et al., 2021). Alternative capture techniques and modified sorbents are also in development and offer potentially higher capture efficiencies, yet issues regarding scalability, energy consumption, toxicity and corrosivity limit their viability. (Bui et al., 2018; Petrovic et al., 2021). The advancement of technologies and systems can, for example, be supported by greater knowledge diffusion, learning-by-doing and knowledge spill-over between global initiatives. These are seen as leading to higher rates of learning which in turn help to overcome a lack of operational experience (Onyebuchi et al., 2018; Beck, 2020; Malhotra and Schmidt 2020). Furthermore, the slow pace with which new $CO_2$ storage sites are identified and developed risks slowing the deployment of CCS (Martin-Roberts et al., 2021), while new capabilities for managing $CO_2$ injection sites are needed to help administer the large data streams associated with real-time monitoring of $CO_2$ plumes (Dean et al., 2020). However, barriers to innovation and knowledge diffusion arise from the need for context-specific capture systems, regional differences in the geological conditions of storage sites, a lack of private sector expertise, and from the long development cycles of CCUS initiatives (Beck, 2020; Malhotra and Schmidt 2020; Lane et al., 2021).

### 3.4. Environmental feasibility challenges

Key *environmental impacts* impact the feasibility of CCUS. For example, $CO_2$ leakage may occur from geological storage sites (Lane et al., 2021) or during $CO_2$ transportation due to pipeline corrosion or equipment failure (Bui et al., 2018; Onyebuchi et al., 2018; Ansaloni et al., 2020). $CO_2$ leakage poses a risk to climate mitigation efforts and is also cause of negative public perception and reduced political support (Cao et al., 2020), while leakage from pipelines in populated areas poses a danger to human health, with $CO_2$ causing the displacement of oxygen in air when released in significant quantities (Onyebuchi et al., 2018). Carbon capture technologies are also linked with toxicity and the release of harmful emission (e.g., ethylene and $NH_3$) during MEA production and degradation (Wang et al., 2022), while ground water contamination is also recognised as a potential environmental impacts, with $CO_2$ injection leading to brine migration and the potential contamination of regional ground water resources (Cao et al., 2020). A side effect of the well-known energy penalty common amongst CCS projects in the power-generating industries (e.g., coal) is caused by the increased fuel consumption needed to offset power loss, which in turn causes an increase in NOx emissions (Wang et al., 2022). In addition, $CO_2$ capture consumes and discharges significant quantities of water and results in increased land-use, which may pose a risk to local ecosystems if managed unsustainably (Sharma, 2018; Ghiat and Al-Ansari, 2021; Wang et al., 2022).

The *mitigation potential* of CCUS is determined by a range of factors, including life-cycle emissions and retention times. Life-cycle emissions arise throughout the CCUS value-chain, including from energy consumption during $CO_2$ capture, during liquefaction and transportation, as well as from the consumption of materials during construction (Wang et al., 2022). Life-cycle emissions may therefore reduce the net effect of carbon capture technologies, especially where fossil fuels are used as the energy carrier (Sharma, 2018; Haszeldine et al., 2018). CCU is also generally an energy-intensive process due to the chemical inertness of $CO_2$ (Akerboom et al., 2021), and despite the commercial case for $CO_2$ utilisation, products such as the electrofuel methanol typically have short retention times compared to long-term geological storage, meaning that $CO_2$ is ultimately released to the atmosphere upon use (Sharma, 2018; Akerboom et al., 2021; Ghiat and Al-Ansari, 2021). The retention time and capacity of the multitude of CCU pathways also varies, with some methods (e.g., mineral carbonation) shown to be limited in their capacity while also being unstable as long-term storage (Woodall et al., 2019).

### 3.5. Institutional feasibility challenges

*Policy* is described as a precondition for CCUS deployment (Ghiat and Al-Ansari, 2021). For example, industrial policy can be used as a powerful signal to industry by communicating future national and international decarbonisation strategies, for which CCUS may be necessary (Beck, 2020). Furthermore, if implemented through a consistent framework, policies can be designed that help promote learning and innovation, and therefore technological readiness (Malhotra and Schmidt 2020; Lane et al., 2021). However, shortcomings relating to international policies around the geological storage of $CO_2$ must be resolved if global storage capacity is to be built out if ambitious decarbonisation targets are to be met in the coming decades (Lane et al., 2021).

*Legislation* and targeted *regulation* are therefore needed to help build momentum around CCUS, with financial legislation and regulations on $CO_2$ emissions deemed key to the Boundary Dam, Snøhvit, Shute Creek and Gorgon CCS projects (Beck, 2020), while clear regulatory guidelines around $CO_2$ injection and monitoring are recognised as a key driver of interest in CCS within the US state of Texas (Martin-Roberts et al., 2021).

*Political support* refers to the degree of support politicians provide to CCUS, which can influence policy, legislation, and regulatory frameworks supporting the deployment of the technologies (Martin-Roberts et al., 2021), although political support can be influenced by vested interest (e.g., Bui et al., 2018). For example, a clear "political agenda" has helped CCS gain momentum in numerous fossil-fuel dependant economies, with Canada, Australia, the U.S, Norway, the UK and the Netherlands all examples where projects have received wide-ranging political and financial support (Bui et el., 2018). However, historically CCS is vulnerable to the ebb and flow of politics, as demonstrated by the Barendrecht project in the Netherlands, which lost political support prior to the 2010 election in the face of growing public opposition (Akerboom et al., 2021).

### 3.6. Organisational feasibility challenges

*Hubs and clusters* relate to concentrations of activities necessary for a working CCUS value-chain and are typically focused on emissions clusters and geological storage networks. Hubs and clusters often depend on the success of a central anchor project, which help to drive the development of shared transportation and storage infrastructures with additional capacity. This in turn allows economies of scale to be realised (Bui et al., 2018) while reducing the risk of cross-chain failure (Beck, 2020), particularly for transportation infrastructure such as pipelines (Onyebuchi et al., 2018).

CCUS feasibility is impacted by various *coordination and management* challenges caused by the scale and co-dependency of both the inherently different parts of the value-chain as well as the diverse nature of the organisations working with the technologies (Bui et al., 2018; Martin-Roberts et al., 2021). For example, CCUS value-chains are associated with long development timescales (Lane et al., 2021) which require experienced and dedicated project management in order to improve collaboration and coordination between different initiatives while reducing cross chain-chain risk (Onyebuchi et al., 2018; Malhotra and Schmidt, 2020). Furthermore, a lack of internal coordination between tasks and responsibilities has been identified as being partly responsible for the failure of the Northern Netherlands CCS initiative (Akerboom et al., 2021). In such situations, a dedicated, privately or publicly owned organisation and associated regulatory agencies may have helped facilitate project activities while providing guidance and an appropriate management framework (e.g., Haszeldine et al., 2018; Bui et al., 2019; Lane et al., 2021).

## 4. Discussion

### 4.1. Strongholds and underrepresented aspects

The meta-review outlines a diverse and multidisciplinary set of factors impacting the feasibility of CCUS. Of the 18 factors identified (Table 2), it is the technical and economic challenges which are most widely presented (Annex 1), thereby echoing the observations by Forster et al. (2020) regarding the prevalence of TEA-focussed research in climate engineering literature. However, it also infers that CCUS deployment continues to be highly challenged by critical technological and economic factors despite continuing advances within the field (e.g., Osman et al., 2021). Abdulla et al. (2021) confirms this in their analysis of historical CCUS projects by identifying three common techno-economic attributes of failed projects from the United States, namely excessive capital costs, varying degrees of technological readiness and performance, and a lack of revenue. Indeed, of the 14 most expensive projects attempted in the United States, 13 were abandoned, while the majority of successful CCUS projects applied proven technologies while monetising $CO_2$ streams (Abdulla et al., 2021). Interestingly, the authors found little correlation between success rate and the amount of financial support received, instead showing that projects dependant on government financing were typically of greater complexity, e.g., by trying to push boundaries through demonstration of unproven technology, and where thus more likely to fail, something echoed by Wang et al. (2022).

As shown, institutional feasibility factors including policy, regulation and legislation represent effective tools for addressing many of the challenges faced in CCUS projects (e.g., Beck, 2020), while a lack of political support can prevent initiatives ever getting off the ground (e.g., Akerboom et al., 2021). The review also reveals how vested interests influence political support (Bui et al., 2018) and how exogenous events, such as the COVID-19 crisis, may lead to changes in policy priorities which lead to the diversion of resources away from CCUS initiatives (Ghiat and Al-Ansari, 2021). Such exogenous 'shock' events, described by the IMF (2003) as events " *beyond the control of the authorities that [have] a significant negative impact on the economy*" (p. 4), likely play a more significant role that the meta-review results imply, with fluctuating support for CCUS also seen following the 2008 recession, the boom in shale gas and, in part, the collapse in the European ETS price in 2011 (Lipponen et al., 2017). Thus, the impact of global events, such as COVID-19, serves also to highlight the linkages between the different groups of feasibility factors identified in this review, in this case the interdependencies between market dynamics, the institutional setting and the resulting financial support. However, recent research by the IMF (2022) into the impact of the COVID-19 crisis on attitudes to climate change concluded that the experience gained from the crisis led to an increase in support for new green recovery policies, highlighting an uncertain and sometimes positive relationship between exogenous events and CCUS feasibility.

The identification of factors relating to coordination and management, as well as, innovation, underscore the relevance of megaproject theory to CCUS practitioners. For example, Flyvbjerg (2006; 2014) describes megaprojects as being characterised by "*long planning horizons and complex interfaces*" as well as by the use of "*non-standard technology and design*", findings echoed by both Onyebuchi et al. (2018) and Malhotra and Schmidt (2020). Furthermore, Flyvbjerg (2014) highlights how the size and nature of megaprojects often result in rotating project managers and a lack of adequate domain knowledge (e.g., Malhotra and Schmidt, 2020). However, absent from this meta-review is the — often negative — influence of multi-actor and multi-stakeholder decision-making, something which Flyvbjerg asserts makes such projects vulnerable to optimism bias, power dynamics or principle-agent behaviours. Thus, CCUS practitioners eager to mitigate such pitfalls may look to megaproject theory to improve interface management and thus minimise cost overruns and project delays (Flyvbjerg, 2014; Edwards and Celia, 2018).

Key social aspects appear underrepresented in the meta-review, even though social factors have proven critical to CCUS deployment (e.g., Akerboom et al., 2021). For example, cultural dimensions impact a population's risk perception and therefore the level of public support for CCUS (Karimi and Toikka, 2018; Witte, 2021), while the social license to operate, a concept identified in only two review papers (Cao et al., 2020; Lane et al., 2021), represents a growing field of study with implications for the deployment of CCUS at the regional scale (Gough et al., 2017; Mulyasari et al., 2021). In this respect, the review papers analysed in this study fail to properly account for a complex series of factors relevant to issues of public perception and the SLO, such as differences in national cultures (Karimi and Komendantova, 2017) and the role of framing and narratives (Mabon and Littlecott, 2016; Whitmarsh et al., 2019; Asayama and Ishii, 2021). Many of these factors are ultimately included in the growing call for research investigating the broader desirability of geoengineering solutions such as CCUS for society (Forster et al., 2020; Waller et al., 2020).

The meta-review identified various environmental risks relating to the deployment of CCUS (e.g., Sharma, 2018; Akerboom et al., 2021; Ghiat and Al-Ansari, 2021). Yet, broader literature highlights additional trade-offs and life-cycle impacts relating to the widespread deployment of CCUS, as well as negative impacts arising from technological lock-in. For example, research indicates that the global consumption of water for hydrogen electrolysis is expected to reach 20.5 billion $m^3$ annually, with desalination expected to play a growing role in meeting this demand (Beswick et al., 2021; Oliveira et al., 2021). Yet, salinity elevation resulting from brine discharge following desalination can be harmful to organisms in both marine and terrestrial ecosystems (Omerspahic et al., 2022). This underscores the need for research tackling the cumulative impacts arising from the global deployment of CCUS to ensure the technologies are deployed sustainably. Furthermore, Koj et al. (2019) show how the use of vehicles powered by hydrogen generated in coal-dependant grids can lead to worse environmental impacts than conventional internal combustion engines, highlighting the importance of the understanding the wider system into which CCUS may be deployed.

Research on technology lock-in is especially underexplored in the review papers analysed. Research on CCUS lock-ins includes specific sectors or technologies (Markusson, 2012; Asayama, 2021), conceptual work (Markusson, 2011) and studies of narratives and debates (Gunderson et al., 2020; Janipour et al., 2021). Technology lock-in occurs when an incumbent technology prevents the development of new transition pathways via a system of path-dependency (Seto et al., 2016). In the case of CCUS, the focus is typically on its use in association with fossil fuel industries and how this may hinder the future deployment of, and investments in, other low-carbon technologies, thereby hindering international climate change efforts (e.g., Shackley and Thomspon, 2012; Fajardy et al., 2019; Howarth and Jacobsen, 2021). However, the application of CCUS to waste incineration facilities can also lead to a system of path dependency, with carbon capture shown to significantly reduce heat recovery (Christensen and Bisinella, 2021), which may in turn lead to more waste needing to be incinerated to meet demand. This may ultimately prevent the emergence of local circular economy initiatives (Van de Berghe et al., 2020) thereby impacting the sustainability of the wider system. Research into the sustainability of a wider set of CCUS technologies, value-chains and sector applications is therefore lacking, and a failure to consider and communicate the potential systemic implications of CCUS deployment at scale ultimately risks eroding the legitimacy of the technologies (e.g., Jijeleva and Vanclay, 2017; Janipour et al., 2021).

### 4.2. *Implications for feasibility frameworks*

The factors identified in the meta-review shown to impact CCUS feasibility are broader than those typically presented by more commonly applied assessment methodologies, such as the PESTEL and TEA frameworks. The criticism levelled at such frameworks when applied to complex technologies like CCS (Pikhola et al., 2017) is therefore supported by the breadth and multidisciplinary nature of the feasibility factors outlined in this paper. The variety of factors is furthermore in line with the criticism of some authors that prevailing "neoliberal" assessment methods have failed when applied to critical and systemic societal challenges, such as climate change (e.g., Markusson et al., 2012; Forster et al., 2020; Viebahn and Chappin, 2021).

The variety of factors identified can thus be seen as an argument for combining elements from highly technical feasibility studies with a broader conceptualisation of the term feasibility, seen from the perspective of society. Here, a STS-inspired approach, as proposed by Markusson et al. (2012) and others (Christiansen and Carton, 2021; Themann and Brunnengräber, 2021), helps to illuminate organisational factors and the embedded nature of CCUS technologies within the structures of society, thereby underscoring the interrelationships between the technical, economic and social aspects of CCUS innovation and coordination.

Another way of strengthening feasibility frameworks for CCUS would be to combine elements of the PESTEL, TEA and STS-inspired frameworks with methods for investigating the sustainability of projects, as required by the EU legislation on environmental assessments (e.g., EU Directive 85/337/EEC). The environmental assessment framework helps project developers by providing insight into a range of environmental and social concerns relating to a project or plan, with significant negative impacts often tackled with a range of mitigation measures. Environmental assessments typically focus on material impacts, such as the impacts to biodiversity or human health. However, the assessment framework described under EU Directive 85/337/EEC can also be used to ensure that the potential impacts of a CCUS project are both thoroughly scoped and assessed for all activities throughout construction, operation and decommissioning, while bringing to light potential negative impacts to a diverse series of factors such as soil contamination, emissions to air and cultural heritage are (Koornneef et al., 2008). Furthermore, it recognises the need to assess both trans-boundary and cumulative effects, which is of great importance to CCUS given the significant role the technologies are projected to play in coming years (e.g., IEA, 2021). Environmental assessment legislation further prescribes public consultation, which could be used more proactively to investigate the social licence of different CCUS technologies across various sector applications.

## 5. Conclusion

In this article we set out to explore the range of different challenges impacting the feasibility of CCUS by performing a meta-review of recent review literature from the past 5 years. Compared to other papers on the feasibility of CCUS, this paper's contribution is an unfolding of various systemic, non-technical and underexplored deployment challenges and a combination of recent developments in literature (and thus indirectly in technology development and increased knowledge of feasibility) covering a range of CCUS technologies.

The results of the meta-review also underscore the multidisciplinary nature of challenges impacting CCUS feasibility and highlight the importance of engineering, innovation and research, social sciences, public policy, geology and the environment, economics, project management and law and governance. The paper provides an overview of a comprehensive range of feasibility factors identified in 22 review papers in recent literature on CCUS and further categorised these factors as economic, social, technological, institutional, environmental and organisational factors. The factors presented here should be viewed as a guide to practitioners and academics alike and should not be viewed as an exhaustive list.

While the exact grouping and classification of factors and categories can be debated, the results provide a basis for reflecting upon current knowledge of feasibility as provided in review literature as well as upon current feasibility frameworks applied in the field of CCUS. The discussion outlined continued challenges around the techno-economic dimensions of CCUS, yet demonstrates the need for key social, organisational and environmental aspects to be unfolded in future CCUS research in order to improve the feasibility of CCUS and ensure the technologies are deployed sustainably, when seen from a society standpoint. Our results therefore answer the call for broadening the scope of CCUS feasibility assessments to avoid what Forster et al. (2020) and Markusson et al. (2020) see as the prevailing focus on techno-economic dimensions and what Pikhola et al. (2017) sees as the simplification of results. The findings of this study are therefore different from similar research, where assessments of feasibility challenges are typically reviewed for isolated projects (e.g., Sara et al., 2015).

Due to the increased maturity of CCUS technologies, a shift from technical demonstration and testing to implementation will be made in the coming decades. This may require a renewed focus on organisational factors and context specific factors in the implementation in order to avoid key pitfalls often associated with so-called megaprojects (e.g., Flyvbjerg, 2014). Experiences from the implementation of more projects as well as increased opportunities for evaluating and monitoring impacts may improve the understanding of feasibility as well as the application of feasibility frameworks in practice.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

We have shared the content analysis of the review papers as supplementary material

## Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.ijggc.2023.103878.

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