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.

Keywords: CCUS; socio-technical systems; feasibility; deployment challenges; techno-economic assessment; sustainability

Highlights:

- 22 reviews of CCUS literature are reviewed for CCUS challenges
- The challenges are grouped into 18 factors in a framework of 7 overall categories
- Technical and economic challenges are most widely presented
- Key social aspects appear underrepresented in the meta-review

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 sources 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 should 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., 2020). 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. Techno-economic analyses (TEA) is likely among the most widespread, 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 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. 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, emphasising its value in integrating the concerns of the public to avoid otherwise unidentified sustainability challenges. Several authors have employed STS in assessments of CCUS feasibility. For example, Markusson et al. (2012) applied the concept and identified the central role of actors, organisations and effective 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, from technology-specific techno-economic challenges to barriers embedded in organisations, institutions and the construct of society. However, despite the large number of review papers tackling different topics within the CCUS field, given that research has called for greater consideration of both systemic and non-technical challenges in assessments of CCUS feasibility, to the knowledge of the authors, there are presently no studies seeking to document, contextualise nor unfold such challenges in a systematic way. The objective of this article is therefore twofold: to synthesise existing review literature to identify the range of challenges shown to impact CCUS deployment, and to unfold those challenges typically underrepresented in CCUS feasibility research, thereby highlighting 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. 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 the 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 CO2 Utilisation and the Journal of Environmental Management (table 1).

Table 1: Review papers on CCUS technologies

Paper	Year	Journal
Wang et al.	2022	Environmental Research
Akerboom et al.	2021	Frontiers in Energy Research
Ghiat and Al-Ansari.	2021	Journal of CO2 Utilisation
Hazra Chowdhury et al.	2021	ChemNanoMat
Lane et al.	2021	Nature Climate Change
Martin-Roberts et al.	2021	One Earth
Petrovic et al.	2021	Microporous and Mesoporous Materials
Alivand et al.	2020	ACS Sustainable Chemistry and Engineering
Ansaloni et al.	2020	International Journal of Greenhouse Gas Control
Beck	2020	Clean Energy
Cao et al.	2020	Energies
Dean et al.	2020	International Journal of Greenhouse Gas Control
Malhotra and Schmidt	2020	Joule
Zhao et al.	2020	Frontiers in Chemistry
Azadi et al.	2019	Sustainability
Galina et al.	2019	Minerals Engineering
Woodall et al.	2019	Greenhouse Gases: Science and Technology
Bui et al.	2018	Energy and Environmental Science
Haszeldine et al.	2018	Phil. Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences
Onyebuchi et al.	2018	Renewable and Sustainable Energy Reviews
Sharma	2018	Carbon Management
Teixeira et al.	2018	Biofuels, Bioproducts and Biorefining

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 2018–2022. 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 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. The full body of results returned using the initial search terms were then screened to identify papers where titles included the word “review”. Unavailable articles were discarded from the results, yielding in total 22 review papers.

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 chapters 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 (e.g. 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, societal technological, institutional, environmental and organisational.

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.

Table 2

Category	**Description**	**Feasibility challenge**
Economic	Factors impacting the economic viability of CCUS, both internal and external to the project	*Cost* *Financial support* *Market drivers* *Business models*
Social	Factors affected by societies' trust, belief and perception of CCUS	*Public acceptance* *Social licence to operate*
Technological	Factors impacting the physical, temporal and spatial implementation of CCUS technologies and systems	*Performance issues* *Geological* *Proximity to infrastructure* *Innovation*

Institutional	Factors describing the political environment and legal infrastructure of a country	*Policy* *Legislation* *Regulation* *Political support*
Environmental	Factors which threaten the environmental value of CCUS technologies and systems	*Environmental impacts* *Mitigation potential*
Organisational	Factors related to how CCUS initiatives are managed and organised within society	*Coordination and governance* *Hubs and clusters*

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 CO2 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 CO2 in the United States (Martin-Roberts et al., 2021), the present global demand for CO2 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, such as how to share and transfer financial risk, the issue of cross-chain default, limitations in existing insurance markets 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., 2019), while questions regarding project financing also persist (Martin-Roberts et al., 2021).

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 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 '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., 2021; 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), declining absorption rates (Wang et al., 2022) and challenges caused by flue gas composition and concentration (Sharma, 2018; Ghiat and al-Ansari, 2021) 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 by uncertainties around as 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 co2 storage capacity too high (Beck, 2020), which this 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 CO2 transportation (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 application, 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 CO2 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 CO2 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 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).

P*olitical support* can ensure that policy, legislation, and regulatory frameworks supporting the deployment of CCUS are developed (Martin-Roberts et al., 2021), although political support can be influenced by vested interest (e.g. Bui et al., 2019). For example, *a* clear "*political agenda*" has helped CCS gain momentum in numerous fossil-fuel dependent 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., 2019). 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).

3.1.5 Environmental feasibility challenges

Key environmental impacts impact the feasibility of CCUS. For example, CO_2 leakage may occur from geological storage sites (Wang et al., 2022) 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 reduce political support (Cao et al., 2020), while leakage from pipelines in populated areas poses a danger to human health, with CO2 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 CO2 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 among CCS projects in the power-generating industries (e.g. coal) is caused by the increased fuel consumption need to offset power loss, which in turn causes an increase in NOx emissions (Wang et al., 2022), while 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, 202; 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). CCU is also generally an energy-intensive process due to the chemical inertness of CO2 (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 limited in their capacity while also being unstable as long term storage mediums term (Woodall et al., 2019).

3.5 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 can 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 governance* 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). Here, dedicated, publicly owned organisation and regulatory agencies could have helped facilitate project activities while providing guidance and an appropriate governance 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. (2020) 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., 2020). Interestingly, the authors found little correlation between success rate and the amount of financial support received, instead showing that projects dependent on government financing were typically of greater complexity and thus more likely to fail on other grounds, 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., 2019) 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 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 governance, as well as, innovation, underscore the parallels between CCUS and the megaproject paradigm. 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 met-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 these pitfalls may choose to look to classical megaproject scholars to avert 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 populations 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 paper (Cao et al., 2021; 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 cimplex 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; Wang et al., 2022). 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-dependent grids can lead to worse environmental impacts than conventional internal combustion engines, highlighting the importance of the wider system in which analysis to 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 and Petersen, 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 EU Directive 85/337/EEC ensures that the impact of a project is assessed for all activities through construction, operation and decommissioning, while further investigating potential negative impacts to a diverse series of factors such as soil, emissions to air and cultural heritage. 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.

The results of the meta-review underscore the multidisciplinary nature of challenges impacting CCUS feasibility and highlight synergies between 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 alilke, 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 support the case for broadening the scope of CCUS feasibility assessments in future to avoid what Forster et al. (2020) describe as a "*focus on relatively narrow 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.

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