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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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*Published in:*

International Journal of Greenhouse Gas Control

*DOI (link to publication from Publisher):*

[10.2139/ssrn.4270412](https://doi.org/10.2139/ssrn.4270412)

*Publication date:*

2022

*Document Version*

Early version, also known as pre-print

[Link to publication from Aalborg University](#)

*Citation for published version (APA):*

Storrs, K. D. P., & Lyhne, I. (2022). A Comprehensive Framework for Feasibility of Ccus Deployment: A Meta-Review of Literature on Factors Impacting Ccus Deployment. Manuscript submitted for publication. <https://doi.org/10.2139/ssrn.4270412>

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# 1 **A comprehensive framework for feasibility of CCUS deployment: A meta-review of** 2 **literature on factors impacting CCUS deployment**

## 5 **Abstract**

6  
7 Carbon capture, utilisation and storage (CCUS) has gained prominence as one of a suite of technologies needed  
8 for mitigating the urgent threat posed by climate change. Despite the significance of CCUS technologies to a  
9 multitude of climate mitigation scenarios, research has identified a series of challenges to deployment, ranging  
10 from cost overruns and technical failures to public opposition. Research has widely documented the range of  
11 techno-economic challenges impacting the feasibility of individual technologies. However, a growing body of  
12 research calls for the feasibility of CCUS to be assessed more holistically, with greater focus on systemic, societal  
13 and other non-technical issues. Through a meta-review of 22 recent multidisciplinary review papers on CCUS,  
14 we identify and explore a comprehensive set of challenges impacting CCUS deployment. The results show a  
15 continued focus on the techno-economic dimensions within literature. However, the meta-review also unfolds a  
16 series of issues receiving less attention in literature, from organisational and environmental challenges to issues  
17 of legitimacy. Overall, this paper contributes to a broader understanding of the critical challenges facing CCUS  
18 projects in the coming decade and provides a framework for a more holistic assessment of climate mitigation  
19 technologies such as CCUS.

20  
21 **Keywords:** CCUS; socio-technical systems; feasibility; deployment challenges; techno-economic assessment;  
22 sustainability

## 24 **Highlights:**

- 25 - 22 reviews of CCUS literature are reviewed for CCUS challenges
- 26 - The challenges are grouped into 18 factors in a framework of 7 overall categories
- 27 - Technical and economic challenges are most widely presented
- 28 - Key social aspects appear underrepresented in the meta-review

29

## 30 1 Introduction

31

32 Carbon capture, utilisation and storage (CCUS) has gained prominence in climate change mitigation policy as a  
33 solution for reducing emissions from industry and fossil-based energy sources to help limit global warming to  
34 1.5°C (IPCC, 2022). The IEA (2021) now estimate that by 2030, globally installed capture capacity within heavy  
35 industries should reach 375 megatons (Mt) of CO<sub>2</sub> per year, yet over the past 10 years the number of active or in-  
36 development projects has stalled (Global CCS Institute, 2016; 2020), with the majority of the 40 Mt of presently  
37 installed capture capacity limited to enhanced oil recovery (EOR) applications (Global CCS Institute, 2019; IEA,  
38 2021). Governments, researchers and intergovernmental organisations have therefore called for a rapid  
39 acceleration in the scale-up and deployment of CCUS (Lipponen et al., 2017; IEA, 2020). However, CCUS  
40 projects display a chequered history, with numerous high-profile technical failures and a legacy of public  
41 opposition and cost over-runs constraining deployment (Sara et al., 2015; Bui et al., 2020). As such, an increasing  
42 body of work has sought to document and address the various challenges impacting CCUS feasibility to help  
43 accelerate deployment of the technologies.

44

45 To avoid or reduce project failures, research has applied a series of frameworks for assessing CCUS projects.  
46 Techno-economic analyses (TEA) is likely among the most widespread, and it provides a quantitative framework  
47 for assessing the technical and economic challenges of different processes, products or services (Zimmerman et  
48 al., 2020). TEA has therefore been extensively used to improve the feasibility of CCUS, resulting in efficiencies  
49 in the processes surrounding the capture, utilisation and storage of CO<sub>2</sub> under different settings (Throneman and  
50 Pizzol, 2019; Gladis et al., 2019; Mikhelkis and Govindarajan, 2020; Kamkeng et al., 2021; Nezam et al., 2021).  
51 However, TEAs have proven insufficient at identifying environmental challenges to CCS deployment (Viebahn  
52 and Chappin, 2021), with results often limited to technical conceptualisations of the environment focussed on life-  
53 cycle emissions (e.g. Fasihi et al., 2019). Furthermore, as argued by Bui et al. (2018), the decades of experience  
54 accumulated internationally makes is clear that “*it is not a lack of technical expertise that is inhibiting the*  
55 *commercial deployment*” (p. 1063). In a similar vein, Forster et al. (2020) criticise the narrow lens through which  
56 climate engineering technologies are typically assessed, describing a prevailing “*focus on relatively narrow*  
57 *techno-economic*” assessments. Forster et al. (2020) further warns that if the prevalence of TEA literature  
58 continues to influence the responses and opinions of expert stakeholders, as their analysis shows, then there

59 remains a risk that important, and as yet underexplored and underreported, deployment challenges may be left out  
60 of decision-making arenas in a reinforcing loop.

61

62 Other frameworks for assessing CCUS technologies have proven useful in highlighting the breadth of challenges  
63 at the project scale. In particular, the application of the risk-management assessment framework PESTEL (e.g.  
64 political, economic, social, technological, environmental and legal; Johnson et al., 2008) to CCS projects highlight  
65 a more comprehensive set of challenges spanning multiple domains (Fozzer et al., 2017; Romansheva and Ilinova,  
66 2019). However, the PESTEL framework is commonly used for the strategic analysis of business objectives,  
67 meaning that project challenges are often described more generally whilst being viewed as obstacles which simply  
68 need to be overcome (Johnson et al., 2008). This has led to criticism being levelled as its application to complex  
69 technologies like CCS (Pikhola et al., 2017).

70

71 As a response to the shortcomings of frameworks such as TEA and PESTEL, Pikhola et al. (2017) suggests  
72 applying a socio-technical systems (STS) approach, emphasising its value in integrating the concerns of the public  
73 to avoid otherwise unidentified sustainability challenges. Several authors have employed STS in assessments of  
74 CCUS feasibility. For example, Markusson et al. (2012) applied the concept and identified the central role of  
75 actors, organisations and effective governance in ensuring effective systems integration at the societal level, while  
76 Christiansen and Carton (2021) and Themann and Brunnengraber (2021) applied STS theory to highlight how  
77 actors influence the 'trajectories' of technologies such as CCS.

78

79 As seen from the literature, the scope of factors shown to impact the feasibility of CCUS projects are diverse,  
80 from technology-specific techno-economic challenges to barriers embedded in organisations, institutions and the  
81 construct of society. However, despite the large number of review papers tackling different topics within the  
82 CCUS field, given that research has called for greater consideration of both systemic and non-technical challenges  
83 in assessments of CCUS feasibility, to the knowledge of the authors, there are presently no studies seeking to  
84 document, contextualise nor unfold such challenges in a systematic way. The objective of this article is therefore  
85 twofold: to synthesise existing review literature to identify the range of challenges shown to impact CCUS  
86 deployment, and to unfold those challenges typically underrepresented in CCUS feasibility research, thereby  
87 highlighting important future research agendas. This is performed via a metareview of recent review papers, with  
88 the ultimate aim of assisting researchers and practitioners tasked with deploying CCUS technologies whilst

89 informing societal debates around how best to ensure a responsible development across society. As such, this  
90 article is guided by the following research question:

91

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

93

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

100

## 101 2 Methodology

102

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

104

### 105 2.1 Aggregation of challenges impacting CCUS deployment

106

107 The aggregation of challenges impacting CCUS projects involved the documentation and categorisation of the  
108 range of issues shown to impact the deployment of the technologies worldwide. This was completed by analysing  
109 recent review papers spanning multiple disciplines and technologies to develop a framework of factors known to  
110 impact feasibility. The framework was developed based on the concept of a meta-review (e.g. Cullen and Turnbull,  
111 2005), with the high number of recent review papers providing detailed syntheses of different technologies, key  
112 themes as well as associated challenges. The framework of factors impacting deployment was revised in an  
113 iterative manner as each review paper was assessed, as outlined by the exploratory grounded-theory approach  
114 described by Strauss and Corbin (1998) and Järvinen and Mik-Meyer (2017).

115

116 The review papers analysed were identified in a literature search described in section 2.2. In total, 22 review  
117 papers were identified, published in the period of 2018–2021. The review papers were published in journals such

118 as the International Journal of Greenhouse Gas Control, One Earth, Nature Climate Change, the Journal of CO2  
119 Utilisation and the Journal of Environmental Management (table 1).

120

121 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

122

123

## 124 2.2 Literature review design

125

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

128

129 First, a search query was performed for English-language papers published between 2018–2022. This range was  
130 selected due to a recent increase in investments planned for new commercial CCUS facilities, which the IEA  
131 (2020) note as more than doubling since 2017, indicating a sharp rise in interest around CCUS and related  
132 technologies. The search was performed using the terms “carbon capture, utilisation and storage” and “carbon  
133 capture and storage” in combination with the words “deployment”, “challeng\*” and “barrier”. Next, papers  
134 classified as review papers were selected, with journal and article title subsequently screened to exclude papers  
135 from unrelated scientific fields or where CCUS technologies were not implied. This was followed by a review of  
136 abstracts to exclude papers where challenges or barriers, or ways of facilitating deployment, were not discussed.  
137 The full body of results returned using the initial search terms were then screened to identify papers where titles  
138 included the word “review”. Unavailable articles were discarded from the results, yielding in total 22 review  
139 papers.

140

### 141 2.3 Data collection

142

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

145

- 146 1. **Scoping:** The 22 review articles identified underwent initial scoping, with relevant sections of text identified  
147 from the contents list and article sub-headings e.g. “Commercialisation of CCS: what needs to happen?” (Bui  
148 et al., 2018) and “Constraints on storage developer confidence” (Lane et al., 2021). Discussion and conclusion  
149 chapters were reviewed in full. Passages of text describing challenges to — or means to accelerate —  
150 deployment were subsequently documented. Next, keyword searches were performed using the terms  
151 ‘challenge’ and ‘barrier’ to widen the field of analysis and identify text missed in the first iteration.
- 152 2. **Data coding:** After relevant passages of text were flagged, keyword identifiers were applied to describe the  
153 deployment challenge using a single phrase or word. For example, a discussion of how subsidies from  
154 government may encourage investment in CCUS projects was labelled as "subsidies".
- 155 3. **Determination of groupings:** The large number of recorded keyword identifiers were synthesised into  
156 common language codings in a continuous and iterative manner. For example, phrases describing the same  
157 issue, e.g. “CO<sub>2</sub> price” and CO<sub>2</sub> pricing”, were unified under “carbon pricing”. Next, keyword identifiers were

158 interpreted and grouped into higher-order thematically related sub-categories, or “feasibility challenges” (see  
 159 the supplementary material file). Here, a phrase which accurately described the range of keyword identifiers  
 160 under such a grouping was selected. This was done using an inductive approach (Given, 2008) to ensure that  
 161 the coded data were contextualised based on observed linkages to other individual or groups of keyword  
 162 identifiers. Codings and sub-categories were discussed between the authors and revised as new data emerged  
 163 (e.g. Järvinen and Mik-Meyer, 2017).

164 **4. Categorisation:** Lastly, the critical deployment challenges were grouped into categories using an iterative  
 165 approach involving discussion between the authors to ensure consistency and a common interpretation for  
 166 the different factors. The 6 categories identified include economic, societal technological, institutional,  
 167 environmental and organisational.

168

### 169 3 Results

170

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

175

176 Table 2

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



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

177

178

179

### 180 **3.1 Economic feasibility challenges**

181

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

189

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

195

196 *Market drivers* also impact the economic feasibility of CCUS, with effective CO<sub>2</sub> pricing needed to ensure a  
 197 penalty for emitting CO<sub>2</sub> (Cao et al., 2020), thereby driving emitters toward mitigation technologies such as CCUS  
 198 (Sharma, 2018; Beck, 2020; Martin-Roberts et al., 2021). Emerging markets for CO<sub>2</sub> are also helping to drive  
 199 interest in the technologies, with CO<sub>2</sub> a crucial feedstock in electrofuels such as methanol, as well as in a range

200 of industrial chemical feedstocks (Teixeira et al, 2019 ;Galina et al., 2019; Akerboom et al., 2021). However,  
201 while EOR has long created a demand for fossil CO<sub>2</sub> in the United States (Martin-Roberts et al., 2021), the present  
202 global demand for CO<sub>2</sub> for a range of CCU products could easily be met by a single state-of-the-art coal-fired  
203 power plant (Bui et al., 2018). Furthermore, the current CO<sub>2</sub> price in established markets such as the EU ETS is  
204 largely seen as inadequate in preventing the release of emissions to air (Haszeldine et al., 2018; Dean et al., 2020),  
205 while investment in CCUS projects may also be disrupted in the face of unexpected global events and fluctuating  
206 markets (Ghiat and Al-Ansari, 2021).

207  
208 There are a lack of commercial *business models* for CCUS, with various factors needing to be overcome to  
209 improve CCUS feasibility, such as how to share and transfer financial risk, the issue of cross-chain default,  
210 limitations in existing insurance markets and uncertainty over liabilities in the event of CO<sub>2</sub> leakage (Bui et al.,  
211 2018; Beck, 2020; Akerboom et al., 2021; Martin-Roberts et al., 2021). Furthermore, new mechanisms for  
212 transferring or minimising the financial risk associated with CCUS value-chains — such as contracts for  
213 difference — are needed to help minimize investor risk in the event of fluctuating CO<sub>2</sub> streams (Bui et al., 2019),  
214 while questions regarding project financing also persist (Martin-Roberts et al., 2021).

215

### 216 3.2 Social feasibility challenges

217

218 The feasibility of CCUS can depend on the level of *public acceptance* the technologies attain, which is affected  
219 by trust in key stakeholders, negative associations between carbon capture and fossil fuel industries, perceived  
220 safety risks and the degree of public consultation (Sharma, 2018; Dean et al., 2020; Akerboom et al., 2021). A  
221 lack of public acceptance has proven historically to be a critical barrier to various CCS initiatives and policies,  
222 with opposition emerging particularly around onshore CCS projects (Akerboom et al 2021), often driven by  
223 concerns over the long-term safety of CO<sub>2</sub> storage, a ‘not in my back yard’ tendency or a lack of knowledge  
224 regarding the technologies (Ansaloni et al., 2020; Martin-Roberts et al., 2021).

225

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

230

### 231 3.3 Technological feasibility challenges

232

233 Research underscores diverse *performance issues* throughout the CCUS value-chain. During the capture process,  
234 significant energy penalties may occur (Alivand et al. 2020), while solvent degradation (Bui et al., 2018),  
235 declining absorption rates (Wang et al., 2022) and challenges caused by flue gas composition and concentration  
236 (Sharma, 2018; Ghiat and al-Ansari, 2021) reduce the overall efficiency of the capture process. The presence of  
237 impurities and water in compressed CO<sub>2</sub> during transportation by pipeline can also result in significant pressure  
238 drops and the precipitation of hydrates, which impacts operational efficiency and may led to blockages (Bui et al.,  
239 2018; Onyebuchi et al., 2018; Ansaloni et al., 2020).

240

241 *Geological* challenges continue to pose significant barriers to the deployment of CCS. A key risk remains the  
242 uneven distribution of suitable storage reservoirs across geologic basins worldwide (Lane et al., 2021), while  
243 operational CCS projects, such as Snøhvit, have been impacted by declining injectivity due to pressure build-up  
244 in the reservoir (Bui et al., 2018). Furthermore, while various national initiatives have mapped theoretical CO<sub>2</sub>  
245 storage volumes (Akerboom et al., 2021), translating this into reliable estimates of subsurface capacity remains  
246 highly challenged by uncertainties around as injection rates, CO<sub>2</sub> dissolution mechanics, permeability and  
247 reservoir pressure, attributes which can only be determined via detailed site analysis (Lane et al., 2021). As such,  
248 the current rate at which geological storage sites are being identified and appraised is considered too slow and  
249 uncertainty around co2 storage capacity too high (Beck, 2020), which this risks slowing the deployment of CCS.

250

251 *Access to infrastructure* represents an important entry barrier for emerging and smaller scale CCUS projects, with  
252 increasing distance between a source of industrial emissions and both storage sites and existing transport  
253 mechanisms resulting in higher costs (Beck, 2020; Martin-Roberts et al., 2021). In a similar vein, the existence of  
254 major pipeline networks in the US, which connect sources of emissions to geological storage sites, represents a  
255 major enabler for CCS, helping to minimise entry costs of CO<sub>2</sub> transportation (Martin-Roberts et al. 2021).

256

257 Greater *innovation* is needed to facilitate the scale-up of projects, from demonstration to full-scale and  
258 technologically mature solutions. For example, the technological readiness level (TRL) differs between  
259 technologies and sector application, with the TRL of monoethanolamine (MEA) CO<sub>2</sub> capture differing depending

260 on which industry the technology is applied to (e.g. the power sector or cement industries differs) (Bui et al.,  
261 2018). Generally, the geological storage of CO<sub>2</sub> has been operating commercially for many years and has a high  
262 TRL (Dean et al., 2020), yet CO<sub>2</sub> storage in coal beds remains commercially immature (Cao et al., 2020). Several  
263 CCU pathways are also approaching maturity, yet wider market penetration remains slow due to cost and  
264 efficiency challenges (Bui et al., 2018; Akerboom et al., 2021). Alternative capture techniques and modified  
265 sorbents are also in development and offer potentially higher capture efficiencies, yet issues regarding scalability,  
266 energy consumption, toxicity and corrosivity limit their viability. (Bui et al., 2018; Petrovic et al., 2021). The  
267 advancement of technologies and systems can, for example, be supported by greater knowledge diffusion,  
268 learning-by-doing and knowledge spill-over between global initiatives. These are seen as leading to higher rates  
269 of learning which in turn help to overcome a lack of operational experience (Onyebuchi et al., 2018; Beck, 2020;  
270 Malhotra and Schmidt 2020). Furthermore, the slow pace with which new CO<sub>2</sub> storage sites are identified and  
271 developed risks slowing the deployment of CCS (Martin-Roberts et al., 2021), while new capabilities for  
272 managing CO<sub>2</sub> injection sites are needed to help administer the large data streams associated with real-time  
273 monitoring of CO<sub>2</sub> plumes (Dean et al., 2020). However, barriers to innovation and knowledge diffusion arise  
274 from the need for context-specific capture systems, regional differences in the geological conditions of storage  
275 sites, a lack of private sector expertise, and from the long development cycles of CCUS initiatives (Beck, 2020;  
276 Malhotra and Schmidt 2020; Lane et al., 2021).

277

### 278 **3.4 Institutional feasibility challenges**

279

280 *Policy* is described as a precondition for CCUS deployment (Ghiat and Al-Ansari, 2021). For example, industrial  
281 policy can be used as a powerful signal to industry by communicating future national and international  
282 decarbonisation strategies, for which CCUS may be necessary (Beck, 2020). Furthermore, if implemented through  
283 a consistent framework, policies can be designed that help promote learning and innovation, and therefore  
284 technological readiness (Malhotra and Schmidt 2020; Lane et al., 2021). However, shortcomings relating to  
285 international policies around the geological storage of CO<sub>2</sub> must be resolved if global storage capacity is to be  
286 built out if ambitious decarbonisation targets are to be met in the coming decades (Lane et al. 2021).

287

288 *Legislation* and targeted *regulation* are therefore needed to help build momentum around CCUS, with financial  
289 legislation and regulations on CO<sub>2</sub> emissions deemed key to the Boundary Dam, Snøhvit, Shute Creek and Gorgon

290 CCS projects (Beck, 2020), while clear regulatory guidelines around CO<sub>2</sub> injection and monitoring are recognised  
291 as a key driver of interest in CCS within the US state of Texas (Martin-Roberts et al., 2021).

292

293 *Political support* can ensure that policy, legislation, and regulatory frameworks supporting the deployment of  
294 CCUS are developed (Martin-Roberts et al., 2021), although political support can be influenced by vested interest  
295 (e.g. Bui et al., 2019). For example, a clear “*political agenda*” has helped CCS gain momentum in numerous  
296 fossil-fuel dependent economies, with Canada, Australia, the U.S, Norway, the UK and the Netherlands all  
297 examples where projects have received wide-ranging political and financial support (Bui et al., 2019). However,  
298 historically CCS is vulnerable to the ebb and flow of politics, as demonstrated by the Barendrecht project in the  
299 Netherlands, which lost political support prior to the 2010 election in the face of growing public opposition  
300 (Akerboom et al., 2021).

301

### 302 **3.1.5 Environmental feasibility challenges**

303

304 Key environmental impacts impact the feasibility of CCUS. For example, CO<sub>2</sub> leakage may occur from geological  
305 storage sites (Wang et al., 2022) or during CO<sub>2</sub> transportation due to pipeline corrosion or equipment failure (Bui  
306 et al., 2018; Onyebuchi et al., 2018; Ansaloni et al., 2020). CO<sub>2</sub> leakage poses a risk to climate mitigation efforts  
307 and is also cause of negative public perception and reduce political support (Cao et al., 2020), while leakage from  
308 pipelines in populated areas poses a danger to human health, with CO<sub>2</sub> causing the displacement of oxygen in air  
309 when released in significant quantities (Onyebuchi et al., 2018). Carbon capture technologies are also linked with  
310 toxicity and the release of harmful emission (e.g. ethylene and NH<sub>3</sub>) during MEA production and degradation  
311 (Wang et al., 2022), while ground water contamination is also recognised as a potential environmental impacts,  
312 with CO<sub>2</sub> injection leading to brine migration and the potential contamination of regional ground water resources  
313 (Cao et al., 2020). A side effect of the well-known energy penalty common among CCS projects in the power-  
314 generating industries (e.g. coal) is caused by the increased fuel consumption need to offset power loss, which in  
315 turn causes an increase in NO<sub>x</sub> emissions (Wang et al., 2022), while CO<sub>2</sub> capture consumes and discharges  
316 significant quantities of water and results in increased land-use, which may pose a risk to local ecosystems if  
317 managed unsustainably (Sharma, 2018; Ghiat and Al-Ansari, 202; Wang et al., 2022).

318

319 The *mitigation potential* of CCUS is determined by a range of factors, including life-cycle emissions and retention  
320 times. Life-cycle emissions arise throughout the CCUS value-chain, including from energy consumption during  
321 CO<sub>2</sub> capture, during liquefaction and transportation, as well as from the consumption of materials during  
322 construction (Wang et al., 2022). Life-cycle emissions may therefore reduce the net effect of carbon capture  
323 technologies, especially where fossil fuels are used as the energy carrier (Sharma, 2018). CCU is also generally  
324 an energy-intensive process due to the chemical inertness of CO<sub>2</sub> (Akerboom et al., 2021), and despite the  
325 commercial case for CO<sub>2</sub> utilisation, products such as the electrofuel methanol typically have short retention times  
326 compared to long-term geological storage, meaning that CO<sub>2</sub> is ultimately released to the atmosphere upon use  
327 (Sharma, 2018; Akerboom et al., 2021; Ghiat and Al-Ansari, 2021). The retention time and capacity of the  
328 multitude of CCU pathways also varies, with some methods (e.g. mineral carbonation) shown to limited in their  
329 capacity while also being unstable as long term storage mediums term (Woodall et al., 2019).

330

### 331 **3.5 Organisational feasibility challenges**

332

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

339

340 CCUS feasibility is impacted by various *coordination and governance* challenges caused by the scale and co-  
341 dependency of both the inherently different parts of the value-chain as well as the diverse nature of the  
342 organisations working with the technologies (Bui et al., 2018; Martin-Roberts et al., 2021). For example, CCUS  
343 value-chains are associated with long development timescales (Lane et al., 2021) which require experienced and  
344 dedicated project management in order to improve collaboration and coordination between different initiatives  
345 while reducing cross chain-chain risk (Onyebuchi et al., 2018; Malhotra and Schmidt, 2020). Furthermore, a lack  
346 of internal coordination between tasks and responsibilities has been identified as being partly responsible for the  
347 failure of the Northern Netherlands CCS initiative (Akerboom et al., 2021). Here, dedicated, publicly owned

348 organisation and regulatory agencies could have helped facilitate project activities while providing guidance and  
349 an appropriate governance framework (e.g. Haszeldine et al., 2018; Bui et al., 2019; Lane et al., 2021).

350

## 351 **4 Discussion**

352

### 353 **4.1 Strongholds and underrepresented aspects**

354

355 The meta-review outlines a diverse and multidisciplinary set of factors impacting the feasibility of CCUS. Of the  
356 18 factors identified (table 2), it is the technical and economic challenges which are most widely presented (Annex  
357 1), thereby echoing the observations by Forster et al. (2020) regarding the prevalence of TEA-focussed research  
358 in climate engineering literature. However, it also infers that CCUS deployment continues to be highly challenged  
359 by critical technological and economic factors despite continuing advances within the field (e.g. Osman et al.,  
360 2021). Abdulla et al. (2020) confirms this in their analysis of historical CCUS projects by identifying three  
361 common techno-economic attributes of failed projects from the United States, namely excessive capital costs,  
362 varying degrees of technological readiness and performance, and a lack of revenue. Indeed, of the 14 most  
363 expensive projects attempted in the United States, 13 were abandoned, while the majority of successful CCUS  
364 projects applied proven technologies while monetising CO<sub>2</sub> streams (Abdulla et al., 2020). Interestingly, the  
365 authors found little correlation between success rate and the amount of financial support received, instead showing  
366 that projects dependent on government financing were typically of greater complexity and thus more likely to fail  
367 on other grounds, something echoed by Wang et al. (2022).

368

369 As shown, institutional feasibility factors including policy, regulation and legislation represent effective tools for  
370 addressing many of the challenges faced in CCUS projects (e.g. Beck, 2020), while a lack of political support can  
371 prevent initiatives ever getting off the ground (e.g. Akerboom et al., 2021). The review also reveals how vested  
372 interests influence political support (Bui et al., 2019) and how exogenous events, such as the COVID-19 crisis,  
373 may lead to changes in policy priorities which lead to the diversion of resources away from CCUS initiatives  
374 (Ghiat and Al-Ansari, 2021). Such exogenous ‘shock’ events, described by the IMF (2003) as events “*beyond the*  
375 *control of the authorities that [have] a significant negative impact on the economy*” (p. 4), likely play a more  
376 significant role that the meta-review results imply, with fluctuating support for CCUS also seen following the  
377 2008 recession, the boom in shale gas and the collapse in the European ETS price in 2011 (Lipponen et al., 2017).

378 Thus, the impact of global events, such as COVID-19, serves also to highlight the linkages between the different  
379 groups of feasibility factors identified in this review, in this case the interdependencies between market dynamics,  
380 the institutional setting and the resulting financial support. However, recent research by the IMF (2022) into the  
381 impact of the COVID-19 crisis on attitudes to climate change concluded that the experience gained from the crisis  
382 led to an increase in support for new green recovery policies, highlighting an uncertain and sometimes positive  
383 relationship between exogenous events and CCUS feasibility.

384

385 The identification of factors relating to coordination and governance, as well as, innovation, underscore the  
386 parallels between CCUS and the megaproject paradigm. Flyvbjerg (2006; 2014) describes megaprojects as  
387 being characterised by “*long planning horizons and complex interfaces*” as well as by the use of “*non-standard*  
388 *technology and design*”, findings echoed by both Onyebuchi et al. (2018) and Malhotra and Schmidt (2020).  
389 Furthermore, Flyvbjerg (2014) highlights how the size and nature of megaprojects often result in rotating project  
390 managers and a lack of adequate domain knowledge (e.g. Malhotra and Schmidt, 2020). However, absent from  
391 met-review is the — often negative — influence of multi-actor and multi-stakeholder decision-making,  
392 something which Flyvbjerg asserts makes such projects vulnerable to optimism bias, power dynamics or  
393 principle-agent behaviours. Thus, CCUS practitioners eager to mitigate these pitfalls may choose to look to  
394 classical megaproject scholars to avert cost overruns and project delays (Flyvbjerg, 2014; Edwards and Celia,  
395 2018).

396

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



408

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

421

422 Research on technology lock-in is especially underexplored in the review papers analysed. Research on CCUS  
423 lock-ins includes specific sectors or technologies (Markusson, 2012; Asayama, 2021), conceptual work  
424 (Markusson, 2011) and studies of narratives and debates (Gunderson and Petersen, 2020; Janipour et al., 2021).  
425 Technology lock-in occurs when an incumbent technology prevents the development of new transition pathways  
426 via a system of path-dependency (Seto et al., 2016). In the case of CCUS, the focus is typically on its use in  
427 association with fossil fuel industries and how this may hinder the future deployment of, and investments in, other  
428 low-carbon technologies, thereby hindering international climate change efforts (e.g. Shackley and Thomson,  
429 2012; Fajardy et al., 2019; Howarth and Jacobsen, 2021). However, the application of CCUS to waste incineration  
430 facilities can also lead to a system of path dependency, with carbon capture shown to significantly reduce heat  
431 recovery (Christensen and Bisinella, 2021), which may in turn lead to more waste needing to be incinerated to  
432 meet demand. This may ultimately prevent the emergence of local circular economy initiatives (Van de Berghe  
433 et al., 2020) thereby impacting the sustainability of the wider system. Research into the sustainability of a wider  
434 set of CCUS technologies, value-chains and sector applications is therefore lacking, and a failure to consider and  
435 communicate the potential systemic implications of CCUS deployment at scale ultimately risks eroding the  
436 legitimacy of the technologies (e.g. Jijeleva and Vanclay, 2017; Janipour et al. 2021).

437

## 438 4.2 Implications for feasibility frameworks

439

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

447

448 The variety of factors identified can thus be seen as an argument for combining elements from highly technical  
449 feasibility studies with a broader conceptualisation of the term feasibility, seen from the perspective of society.  
450 Here, a STS-inspired approach, as proposed by Markusson et al. (2012) and others (Christiansen and Carton,  
451 2021; Themann and Brunnengräber, 2021), helps to illuminate organisational factors and the embedded nature of  
452 CCUS technologies within the structures of society, thereby underscoring the interrelationships between the  
453 technical, economic and social aspects of CCUS innovation and coordination.

454

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

## 468 5 Conclusion

469

470 In this article we set out to explore the range of different challenges impacting the feasibility of CCUS by  
471 performing a meta-review of recent review literature from the past 5 years.

472

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

480

481 While the exact grouping and classification of factors and categories can be debated, the results provide a basis  
482 for reflecting upon current knowledge of feasibility as provided in review literature as well as upon current  
483 feasibility frameworks applied in the field of CCUS. The discussion outlined continued challenges around the  
484 techno-economic dimensions of CCUS, yet demonstrates the need for key social, organisational and  
485 environmental aspects to be unfolded in future CCUS research in order to improve the feasibility of CCUS and  
486 ensure the technologies are deployed sustainably, when seen from a society standpoint. Our results therefore  
487 support the case for broadening the scope of CCUS feasibility assessments in future to avoid what Forster et al.  
488 (2020) describe as a “*focus on relatively narrow techno-economic*” dimensions and what Pikhola et al. (2017)  
489 sees as the simplification of results. The findings of this study are therefore different from similar research, where  
490 assessments of feasibility challenges are typically reviewed for isolated projects (e.g. Sara et al., 2015).

491

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

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