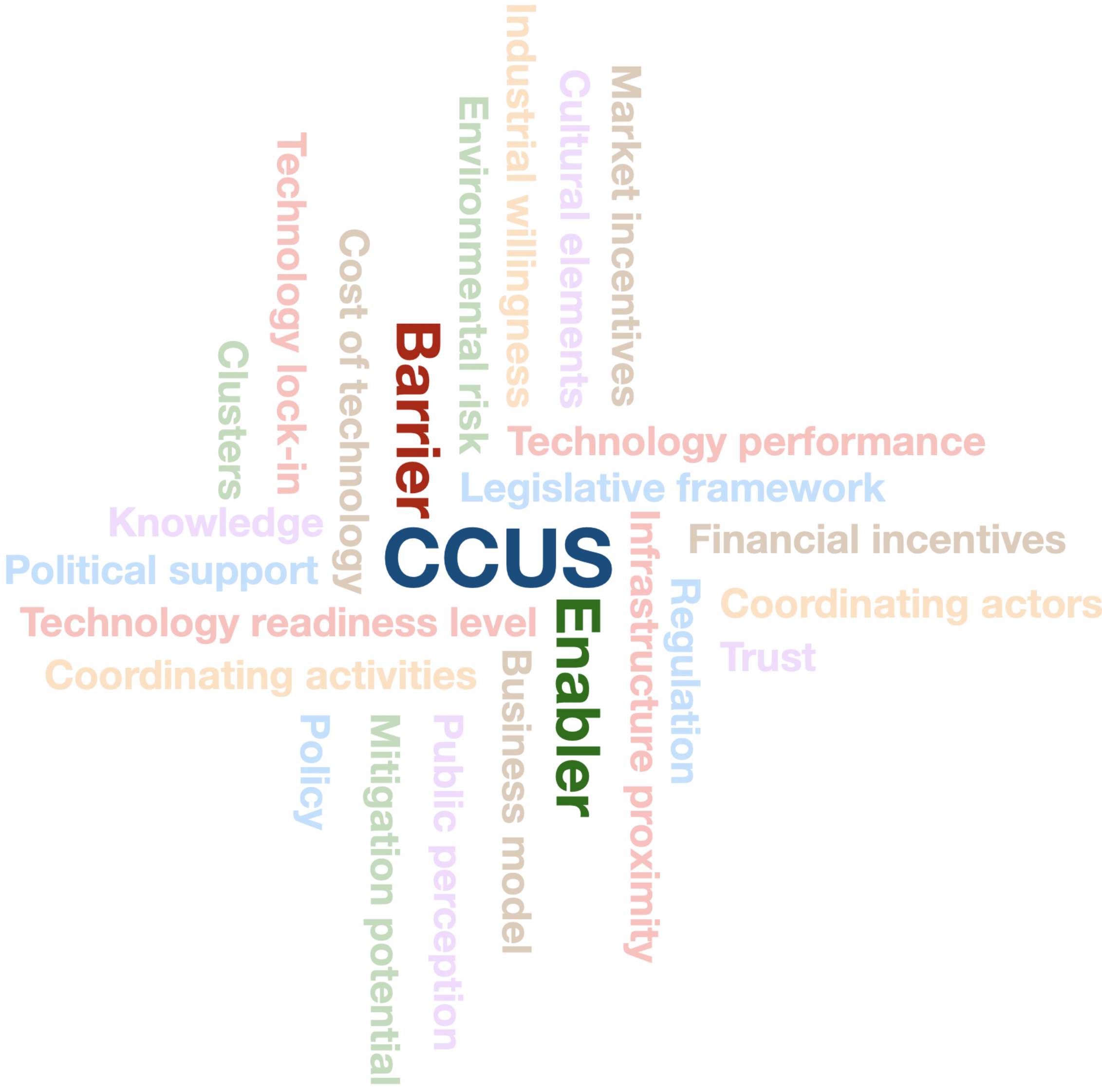
Exploring the feasibility of carbon capture, utilisation and storage in Denmark



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STUDENT REPORT

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Exploring the feasibility of carbon capture, utilisation and storage in Denmark.

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Synopsis:

This study investigates barriers and enablers impacting the feasibility and deployment of CCUS projects on a global scale. The analysis identifies 20 influencing factors in literature in a global perspective to develop a conceptual framework for assessing CCUS feasibility in different settings. These factors are further contextualised, expanded upon and validated through interviews with European CCUS practitioners, which highlights significant aspects absent in literature as well as additional influencing factors. The third part of the analysis investigates the possibility of applying international experiences to an assessment of the feasibility of CCUS in a Danish context. Based on the analysis, possible uncertainties and areas of further research are explored and discussed. Finally, the study concludes that, whilst national context is a significant factor in deploying CCUS, international experiences can help prevent previous mistakes by acting as a guide for the technology in Denmark.

Page numbers: 82
Appendices: 3
Supplementary appendices: 3
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Preface

Reading guide

It is recommended that this report should be read in a chronological order. For source references the Harvard method has been used. A comprehensive list of references is located on page 66. The appendices of the study has been divided into two, for privacy reasons, with a set of supplementary appendices located in a separate document (Appendix D-F).

To guide the reader, a visualization of the study, research questions and methods, is located in chapter 2 and shown in figure 2.1 on page 5.

List of abbreviations

BECCS = Bioenergy with carbon capture and storage
CCS = Carbon capture and storage
CCU = Carbon capture and utilisation
CCUS = Carbon capture, utilisation and storage
CO_2 = Carbon dioxide
DAC = Direct air capture
DCCC = Danish Council on Climate Change (Klimarådet)
EOR = Enhanced oil recovery
ETS = Emissions trading system
GHG = Greenhouse gas
IPCC = The Intergovernmental Panel on Climate Change
MEA = Monoethanolamine
Mta = Mega tons a year
Mt = Mega tons
NGOs = Non-governmental organisations
NPOs = Non-profit organisations
Ptx = Power-to-X
TCO_2/y = Tonnes of CO_2 per year

Summary

Klimaforandringer udgør en trussel for menneskeliv såvel som plante- og dyreliv, og global opvarmning medfører stigende forekomster af naturkatastrofer og accelererer tab af levesteder over hele planeten. Klimaforandringerne er længe blevet tilskrevet menneskelige aktiviteter, og tung industri er årligt ansvarlig for 80% af globale drivhusgasudledninger. Til trods for et ønske om at reducere udledningen af CO_2 er tung industri fortsat voksende (60% siden 1990). Dette har medført en øget politisk bevågenhed, og i 2015 underskrev størstedelen af verdens nationer Parisaftalen, som har til mål at holde den globale opvarmning under 2°C. Efterfølgende, i 2019, præsenterede Danmark 'den mest ambitiøse klimalov i verden', hvori det lød at den nationale CO_2 udledning skulle reduceres med 70% inden 2030 (i forhold til udledninger i 1990). Klimarådet har henvist til at CO_2 fangst, brug og lagring (CCUS) teknologier har potentiale til at reducere Danmarks CO_2 udledninger, som et af flere midler. Men på trods af denne henvisning er der endnu ikke fremlagt en national strategi på området. Derudover, er CCUS projekter globalt set faldende siden 2010.

Med afsæt i denne undren søger dette studie at besvare følgende problemformulering:

Hvordan kan internationale erfaringer med CCUS anvendes til at forstå/vurdere muligheden for sådanne projekter i Danmark?

For at kunne besvare problemformuleringen er der i den første del af analysen udarbejdet et systematisk litteraturstudie, som har til formål at undersøge kendte faktorer som har inflydelse på udviklingen af CCUS projekter i en global kontekst. Gennem databasen, SCOPUS, er der identificeret 255 akademiske artikler dateret fra 2010 frem til tidspunktet for litteraturstudiet, af de 255 akademiske artikler blev 63 udvalgt som værende relevante efter gennemgang af henholdsvis overskrifter og abstracts. Udover det systematiske litteraturstudie af akademiske artikler, er der benyttet grå litteratur fra internationale organisationer som arbejder indenfor feltet til at understøtte resultaterne fra den akademiske litteratur. På baggrund af litteraturstudiet blev der udarbejdet et rammeværktøj, som afspejler 20 faktorer med indflydelse på CO_2 fangst fordelt på seks kategorier: sociale, økonomiske, politiske, miljømæssige, organisatoriske og teknologiske. Disse faktorer er gennem litteraturen alle påpeget som værende enten en katalysator eller en barrierer i implementeringen af CCUS projekter.

Anden del af analysen søger at kontekstualisere faktorerne som blev identificeret i literatur studiet. Dette gøres gennem semistrukturerede interviews med praktiserende Europæiske CCUS projekter, for at undersøge deres erfaringer med de 20 identificerede faktorer, og i hvilken grad de oplever dem som barrierer eller katalysatorer. Studiet bærer præg af en 'grounded theory'-tilgang, og derfor startes interviewene med eksplorative spørgsmål hvor informanterne kan udtrykke egne erfaringer og opfattelser. Herefter introduceres elementer af samskabelse, da rammeværktøjet præsenteres og diskussionen fortsætter med afsæt i informantens tidligere svar og eventuelt nye refleksioner. Som resultat af 6 interviews i anden del af analysen opdateres og udvides rammeværktøjet og teknologiske lock-ins of industrial vilje tilføjes. Samtidig udledes

det, at alle faktorer ikke nødvendigvis har samme betydning, og at kontekst spiller en stor rolle i implementeringen af disse CCUS projekter.

Afslutningsvis sættes faktorerne fra internationale erfaringer, både praktiske og fra litteraturen, i en dansk kontekst, og forskellige udfordringer og usikkerheder i Danmark belyses. Hertil er der udført semistrukturerede interviews med danske interessenter for at få indsigt i hvordan CCUS bliver opfattet i Danmark, og for at kortlægge eventuelle udfordringer.

Studiet konkluderer, at internationale erfaringer med CCUS kan bidrage ved at give et indblik i hvordan forskellige faktorer påvirker implementeringen af CCUS-projekter. Undersøgelsen af internationale erfaringer kan give en unik indsigt i, hvordan samspillet mellem faktorerne har stor indlydelse på om de udvikler sig til barrierer eller katalysatorer, samt hvordan kontekst har indflydelse på forskellige faktorer. Studiet konkluderer ydermere, i form af et hierarkisk rammeværktøj, at de politiske, økonomiske og sociale faktorer på nuværende tidspunkt har stor indflydelse på implementeringen af CCUS projekter. De udgør derfor de fundamentale faktorer, som må tages til overvejelse. Dernæst opfattes de miljømæssige og organisatoriske faktorer som værende essentielle i at optimere teknologien i relation til miljøpåvirkning, energiforbrug og omkostninger. Slutteligt kan det konkluderes, at de teknologiske faktorer ikke alle har lige betydelig indflydelse på projekterne. Flere Europæiske informanter anser teknologien for værende moden, og derfor klar til brug i større scala end tilfældet er på nuværende tidspunkt.

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Introduction 1

Climate change represents an urgent threat to human life as well as to marine and terrestrial ecosystems, with global warming leading to an increasing occurrence of natural disasters and accelerated habitat loss across the planet [IPCC, 2018]. The Intergovernmental Panel on Climate Change (IPCC) have long recognised direct and indirect human activities as being responsible [IPCC, 1992], with key industries responsible for approximately 80% of annual greenhouse gas (GHG) emissions [European Commission, 2020b]. GHG emissions alter the atmospheric composition beyond what is expected to occur naturally [ClientEarth, 2020] and since the 1990s, annual emissions from both energy and heavy processing industries have risen 60% [IEA, 2020b].

In recognition of the growing threat that climate change poses, there has been an increase in international commitments around policies aimed at drastically reducing emissions [e.g. the EUs 2050 climate neutrality target; European Commission, 2020a]. Presently, national strategies vary widely, but most are guided by the Paris Agreement, signed in 2015 and centred on keeping global temperature rises well below 2°C compared to pre-industrial levels [IPCC, 2018]. Various climate mitigation strategies have emerged, with much focus on the decarbonisation of global energy systems by replacing fossil fuels with renewable energy technologies. The EU aims to increase the share of energy generated from renewable technologies to between 38–40% by 2030 [Parnell, 2020], whilst outside of the EU, countries like Canada are also investing heavily with a target of 90% renewable energy generation by 2030 [C2ES, 2020]. However, the decarbonisation of heavy industry remains more problematic due to a reliance upon fossil fuels for thermal energy generation in sectors such as steel, iron and cement [Verma et al., 2020]. Collectively, these industries emit 14% of global emissions each year which is set to rise as demand for raw materials increases toward 2050 [OECD, 2019]. This has led to an increasing focus on the role that breakthrough technologies like Carbon Capture, Utilisation and Storage (CCUS) can play in emissions abatement programs worldwide.

1.1 CCUS: developments and emerging interests

CCUS is a suit of technologies which capture CO_2 emissions and transports them for geological storage or chemical conversion (e.g. power-to-x; Ptx) [IEA, 2020a] (figure 1.1). CCUS works by capturing CO_2 prior to (pre), during (oxy-fuel), or after (post) the combustion of carbon-based fuels during power generation or industrial processes. The most widely deployed technology is post-combustion chemical absorption, where CO_2 is removed from flue gases using monoethanolamine (MEA) solutions [Bui et al., 2018]. Following capture, CO_2 is then compressed to enable safe and efficient transport after which it is then delivered to a suitable geological storage site [IEA, 2020a] or a facility where it is utilised in synthetic products, such as 'green hydrogen' [Bui et al., 2018], which is the result of converting CO_2 from non-fossil resources into hydrogen.

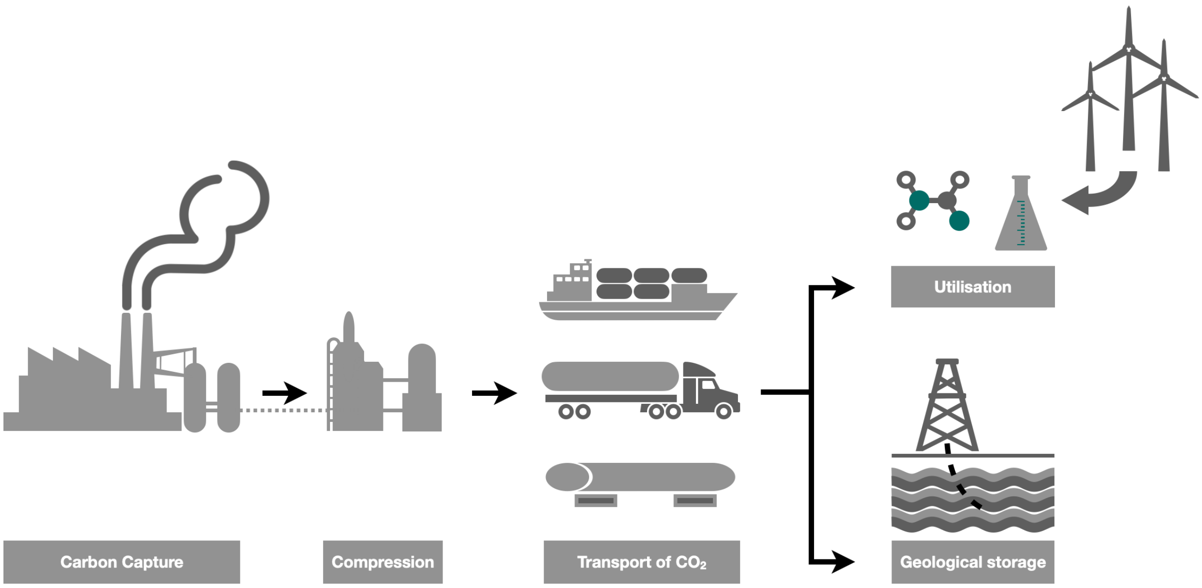

Figure 1.1. Simplified CCUS value-chain. CCUS begins by capturing CO_2 emissions from source, before being compressed for transportation. CO_2 is then typically transported by ship, truck or pipeline — depending on the volume — to a geological storage site or utilisation facility.

Widely viewed as a recent breakthrough technology, carbon capture and storage (CCS) has in fact been in operation since 1972, with CO_2 from natural gas at the Val Verde Natural Gas Plant, USA, still captured, transported and used for enhanced oil recovery (EOR) [Global CCS Institute, 2020a]. CCS is therefore proven as a commercial technology when coupled to extractive industries, even though the net impact on emissions to the atmosphere from EOR remains in doubt [e.g. IEA, 2019]. CCS as a pure climate abatement technology, however, was first widely discussed following the publication of the IPCC [2005] report on CCS and subsequently built on over the following decade. For example, the IEA [2013] showed that globally CO_2 capture would need to reach 2000 megatons per year (Mta) by 2030 in order to stay on track with the commitments of the Paris Agreement. This was corroborated by the IPCC [2018], who highlighted the pivotal role of CCS in three out of four integrated assessment models, which model climate mitigation scenarios in line with a 2°C warming.

In response to growing climate concerns and the view that CCUS is now essential, various initiatives are emerging across Europe. In Norway, Europe's first full-chain CCS project is currently being built, with plans to capture 800,000 tonnes of CO_2 per year (tCO_2/y) [Gassnova, 2020]. In the UK, a national "CCUS Deployment Pathway" strategy as well as several active projects are in development (e.g. Zero Carbon Humber, Acorn CCS, Net Zero Teeside), with a combined 25 Mta of CO_2 targeted for capture by 2030 [Global CCS Institute, 2020c]. Similarly, in the Netherlands, CCS forms a key part of their decarbonisation strategy, with the Porthos project aiming to capture and store 2.5 Mta from the Rotterdam port area [Porthos, 2021a]. CCUS has also received significant attention in Denmark, with the governments recently published climate roadmap [KEFM, 2020] identifying between 4–9 million tonnes of CO_2 suitable for carbon capture.

Following its publication however, the Danish Council on Climate Change (DCCC: Klimarådet) criticised the lack of concrete plans, underpinning the governments strategy and highlighted a massive 'shortfall' of 20 Mt of CO_2 emission for which no plans currently exist [DCCC, 2021b]. The DCCC concluded that the Danish government set too much focus on "unproven technologies" (e.g. CCUS) and drew attention to a range of well known issues needing further exploration if CCUS is to be realised as a feasible emissions reductions strategy in Denmark [DCCC, 2021b].

1.2 Problem formulation

CCUS has been described by the DCCC as having promising potential for reducing GHG emissions in Denmark and have recommended that Danish society prepares for a future in which the technology will play a significant role [DCCC, 2020]. Additionally, with an expected cost of 1000 DKK/tCO_2 captured, transported and stored, the DCCC estimates that the technology comes at an affordable price compared to alternative mitigation methods, echoing similar findings made by the IPCC [2018]. Yet CCUS is a technology which displays a checkered history in terms of its success, with numerous high profile examples showing technical failures and repeated cost overruns [Bui et al., 2018]. External landscape factors have also been shown to impact its feasibility, with interest in CCS foundering after the financial crash and the collapse of the EU emissions trading system (ETS) in 2011 [Lipponen et al., 2017]. Today, there are 61 CCS projects either in operation or development compared to 77 in 2010, with the current capacity of existing CCS systems limited to just 40 Mta [Global CCS Institute, 2020a, 2016a]. This backwards trajectory underscores the vulnerability of CCUS to a range of factors. Aside from widely documented issues regarding the technical complexity [Diego et al., 2017] and cost of the technology [Sara et al., 2015], studies have shown how the feasibility of CCUS is also impacted by highly contextual issues which differ between countries [e.g. Stigson et al., 2012; Karimi and Toikka, 2018]. For example, in 2007 the Swedish energy operator, Vattenfall, identified that Nordjyllandsværket coal fired power plant was in close proximity to a suitable geological storage site at Vedsted, 30 km west of the power plant [Dalhoff et al., 2011]. However, due to intense public opposition in the area, combined with a hesitancy from government to commit to CCS until it had been successfully demonstrated in other countries, the application by Vattenfall was rejected in 2011 [Ritzau, 2011].

10 years on and the Danish government is now finalising a strategy for the deployment and development of CCUS projects in Denmark. Yet Pihkola et al. [2017] discusses how any decision to invest in CCS should be based not only on techno-economic assessments, but also on environmental and social factors understood in the context of a particular setting. Failure to account for the breadth and contextual nature of issues impacting CCUS therefore risks delaying its deployment further, or deploying without consideration of the long-term feasibility for society [Gough et al., 2017]. The previous two decades of international CCUS attempts and failures therefore provides a valuable source of case information which can be used to identify and assess CCUS feasibility factors in order to guide the Danish government in the years to come. Furthermore, the most recent phase of projects currently emerging in Europe represent an opportunity to explore a practitioner-centred view of different contextual perspectives, useful for predicting how certain issues may present themselves in Denmark.

Whilst acknowledging the importance of CCUS to national climate targets, the DCCC also emphasise that carbon capture is but one of many mitigation technologies, all of which are needed to reach national climate goals, and state that the use of CCUS must not justify a continued and inconsiderate use of fossil fuels [DCCC, 2020]. This points to an emerging debate around technology and carbon lock-in, which occur when the deployment of a particular technology prevents the adoption of more suitable or sustainable alternative [Unruh, 2000]. Janipour et al. [2021] states that technology lock-in associated with the fossil fuel industry may lead to a reduction in investment in other low-carbon technologies, whilst Seto et al. [2021] underscores the need for decision-makers to thoroughly understand how and when lock-ins arise. Despite its potential, many are hesitant in believing that an undeveloped technology will be an 11th hour saviour [Nissen, 2020; Sæhl, 2020]. Members of Greenpeace Denmark have criticised the Danish government for their lack of ambition to make yearly reductions to GHG emissions, rather than having linear reductions through the better part of the coming decade, and relying on uncertain technological solutions [Nissen, 2020]. One researcher goes so far as to say that the governments ambition of capturing 4-9 million tons of CO_2 a year by 2030 is far beyond what is possible [Sæhl, 2020]. This uncertainty calls for an investigation into the feasibility of CCUS in Denmark, leading to the following research question:

How can international experiences around carbon capture, utilisation and storage be used to assess the feasibility of such projects in Denmark?

Research design 2

To guide the study and help answer the primary research question, a research design and three sub-questions were developed (figure 2.1).

How can international experiences around carbon capture, utilisation and storage be used to assess the feasibility of such projects in Denmark?

Sub-questions:

1. Which factors influence the feasibility of CCUS projects globally?
2. How do European practitioners experience barriers and enablers to CCUS projects?
3. What are the issues and uncertainties facing CCUS projects in Denmark?

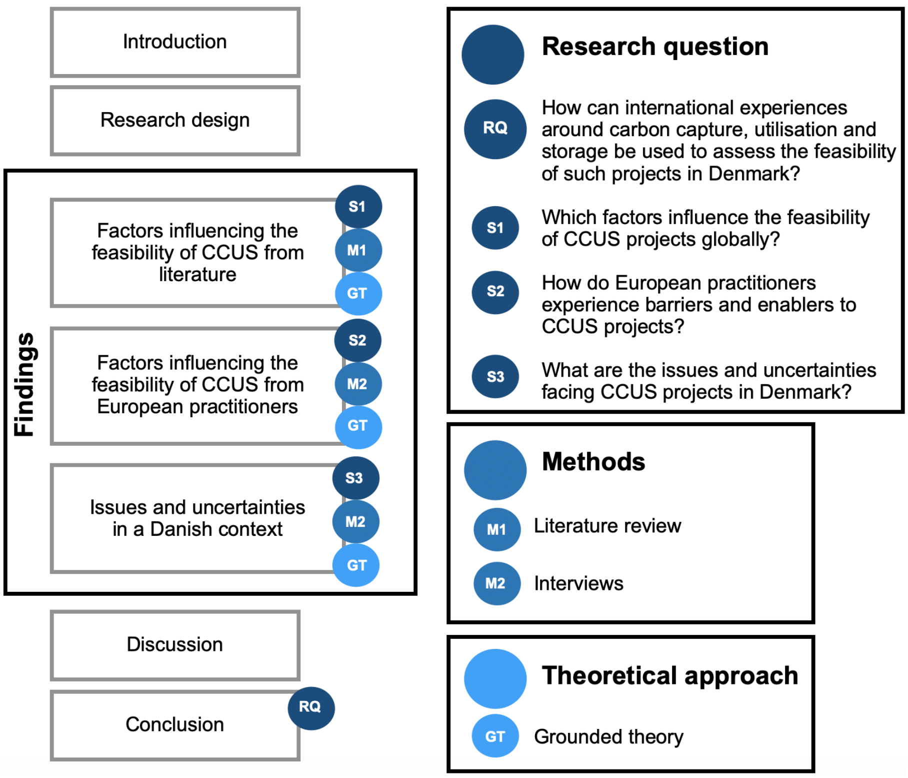

Figure 2.1. A visualisation of the report structure, as well as corresponding research questions and methods.

Preliminary research drew attention to several key areas of interest around deployment of CCUS, related to decline in number of projects on an international level over the past ten years [Lipponen et al., 2017; Global CCS Institute, 2016a], a surprising observation highlighting the complexity of CCUS projects and their vulnerability to different factors. The following sub-question was therefore developed to help assess how and why CCUS project either fail or success:

1. What factors influence the deployment and development of CCUS project globally?

The first sub-question was investigated through a comprehensive literature review designed to identify a range of different factors influencing the feasibility of CCUS projects worldwide (figure 2.1). Here, the term feasibility draws on the research of Lund [2014] who states that in *"socioeconomic feasibility studies, the question is whether a project is feasible to society as a whole"*. The understanding and terminology of feasibility was therefore expanded beyond traditional techno-economic aspects, typically associated with business related feasibility studies, to include all barriers or enablers to CCUS from a project or societal perspective. The systematic literature review included only academic literature but was supplemented by grey literature, with the search and review methodology elaborated in section 3.1. Grey literature, in the form of technical reports published by organisations focusing on CCUS, were used due to a common trend where academia tends to be a few years behind grey literature in emerging fields of study [Jewell, 2018]. Understanding the comprehensive range of factors and why they emerge is important, as public debates on CCUS are often centred around its cost and how the technology is assumed to still be technologically immature [Madsen and Svendsen, 2020]. The data collected in the literature review was categorised and contextualised in a framework presenting 20 different influencing factors divided into six categories.

The second sub-question explores how the factors identified from sub-question 1 are experienced by different European CCUS practitioners, with earlier studies pointing toward the importance of national setting [Stigson et al., 2012]. By analysing how specific enablers and barriers to CCUS deployment are experienced in different European countries, the importance of contextual factors could be assessed, with research guided by sub-question 2:

2. How do European practitioners experience barriers and enablers to CCUS projects?

Through interviews, sub-question 2 investigated CCUS projects in multiple European countries, with the aim of assessing how the national context has impacted the potential success or failure of any domestic projects. Using the results from sub-question 1, an interview guide (Appendix C.1) was generated to explore practitioner experiences in relation to barriers and enablers, allowing for open-ended discussions to let previously unidentified enablers or barriers surface. After collecting general data from literature, and combining the findings with specific contextual data gained from interviews, the focus of the study shifts to the feasibility of CCUS projects in Denmark:

3. What are the issues and uncertainties facing CCUS projects in Denmark?

The feasibility from a Danish societal perspective was explored using the framework developed and refined from international experiences (e.g. sub-questions 1 and 2). Furthermore, the third chapter drew on interviews with key stakeholders in Denmark (Appendix C.2) and was supplemented using peer-reviewed articles and grey literature (e.g. newspaper articles and policy documents) (figure 2.1).

2.1 Grounded theory

This study is guided by grounded theory, which dictates a exploratory approach to research, where data collection and analysis are conducted concurrently [Järvinen and Mik-Meyer, 2017]. This means that data from both literature and each interview is used to guide the research in its subsequent steps, and the researchers avoid the burden of large amounts of unfocused data not leading to new discoveries and directions [Järvinen and Mik-Meyer, 2017]. Grounded theory places itself between positivism and critical rationalism, and its ontology believes that data can be observed [Glaser, 2002; Brinkmann and Tanggaard, 2020]. The aim of grounded theory is to generate theories through inductive research [Glaser and Strauss, 1967], letting the data speak for itself to tell its own story. Grounded theory is therefore an iterative process that seeks to create and compare theories until the collected data is sufficient to answer the research question [Glaser and Strauss, 1967]. By continuously realising that exploration into new contexts is necessary, interim theories can be adapted and refined when new data becomes available.

The grounded theory approach in this study was supplemented with elements of knowledge co-creation in the second and third parts of the analysis. Knowledge co-creation is a collaborative process wherein multiple actors generate data and value through interactions. Knowledge co-creation is recognised as an important tool for developing new conceptual frameworks based on insights which can ultimately be tested in diverse contexts [Galvagno and Dalli, 2014]. The use of knowledge co-creation is further described in section 3.2.

As illustrated in figure 2.2, the first iteration of data collection consisted of a literature review through which coding and data analysis identified an interim theory. Despite the comprehensiveness of the method, the literature review showed results of historical experiences with CCUS as well as more theoretical discussions. Through the process of theoretical sampling, the results from chapter 4 were shown to be insufficient in contextualising how different factors may impact CCUS feasibility in Denmark. Therefore, the first interim theory was explored in further detail through experiences of current European CCUS practitioners, with the purpose of identifying the most urgent issues today. The second iteration consisted of interviews with multiple European CCUS projects, with the data highlighting the significance specific aspects, whilst drawing attention to previously unidentified factors that may arise, leading to a second interim theory. The third iteration consisted of interviews with Danish stakeholders and contextual data from Denmark. These focused around the perceived feasibility of CCUS in Denmark towards to 2030 climate target.

The framework outlined in figure 2.2 provides the rationale for the research design and therefore led the research. This study followed three steps which also correspond to the number of sub-questions used to answer the research question:

1. The identification of critical factors impacting the deployment of CCUS from a global perspective. The data was collected through a literature review described in (section 3.1).
2. Results from the literature review were used to create and shape an interview guide for chapter 5. The interviewees describe their experiences, before discussing the relevance of the factors identified from literature. The data was used to evaluate and expand the framework where relevant.
3. Interviews with Danish stakeholders explored key issues in deploying CCUS in Denmark. The data was used to create a final framework, presenting factors influencing CCUS in a hierarchical format relevant to Danish CCUS practitioners (chapter 6 and chapter 7).

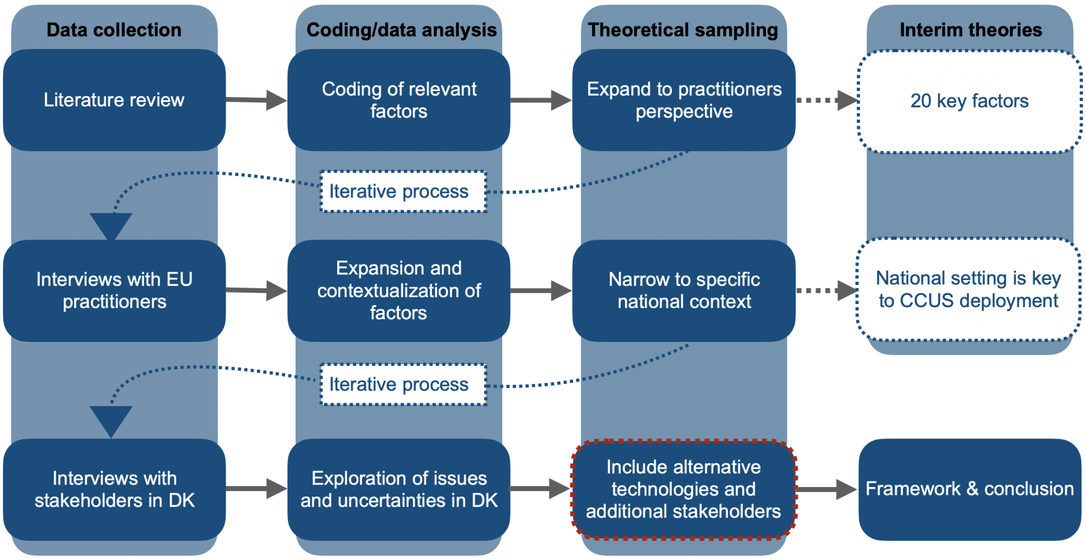

Figure 2.2. An illustration of the iterative grounded theory process, as conducted throughout the study. The red, dashed, line represents ideas for further research, and are not conducted in this study.

All the steps are deemed necessary and equally important in terms of answering the research question. However, using grounded theory comes with limitations that researchers should be aware of. For example, grounded theory methods often generate large amounts of data, which need to be systematically organised. Yet critics highlight the lack of standard methods for coding and categorising data [Bryant and Charmaz, 2007]. Furthermore, the recruitment of participants and subsequent data collection can be time-consuming, which in some cases can lead to small sample sizes[Glaser, 2002]. Theories are created based on patterns in the data, and the method opens itself up to questions about whether additional data collection would change the results. Furthermore, it should be noted that there is a possibility of the researchers being biased when conducting the interpretation of the data due to what Bryant and Charmaz [2007] describe as the embedded nature of the researcher. Ultimately, the theory should be able to lead back to the data [Glaser and Strauss, 1967]. The next chapter will explain how the data used in the project was gathered and an explanation of how the literature review and the interviews were conducted will be made.

Methodologies 3

3.1 Literature Review

The aim of performing a literature review is to identify and investigate the variety of different factors which act as enabling forces or barriers to the feasibility of CCUS projects in a global context. The results are then used to develop a framework classifying the range of different factors that can impact CCUS projects, with the framework subsequently used to guide the interviews with developing and established CCUS projects across Europe.

To ensure a transparent and replicable literature review [Snyder, 2019], a systematic step-wise approach was adopted, which was further divided into two distinct stages: 1) the identification and assessment of peer-reviewed articles (see appendix A), and 2) the identification and assessment of publications from grey literature.

Peer-reviewed articles

Scopus was chosen as the search database to perform the literature review due to its status as the largest digital database of peer-reviewed abstracts and citations. Only English language papers were included, whilst the time-frame was limited to 2010–2021. The reason for selecting 2010 as the lower limit for the publication date relates to commitments by G8 leaders to have facilitated 20 demonstration-scale CCS projects by 2010. This target was designed to speed up the widespread deployment of CCS in time for 2020 [IEA, 2010], with 2010 considered a turning point in the degree of exposure and recognition achieved by CCUS technology [Lipponen et al., 2017]. However, the opposite happened, and CCUS projects have been en decline since 2010.

Next, a thorough search-string was developed based on terminology relevant to the subject under investigation, with both "carbon capture and storage", "carbon capture and utilisation" and "carbon capture, utilisation and storage" incorporated (figure 3.1). As the purpose of the review was to identify both enabling factors and barriers to the deployment of CCUS projects (i.e. issues impacting its feasibility), naturally both of these terms were incorporated. Additionally, in an effort to broaden the search, and in recognition of the fact that not all authors discuss the subject using the same terminology, synonyms and similar words to "enabling" and "barriers" were incorporated into the search string. These included "challenges", "drivers", "obstacles", "opportunities", "risk" and "deployment". This contributed to the inclusion of more, and potentially equally relevant and important, factors impacting the deployment of CCUS projects worldwide. Utilising these criteria in an advanced search in the Scopus database returned 255 articles, which were subsequently assessed through three steps to further determine their relevance.

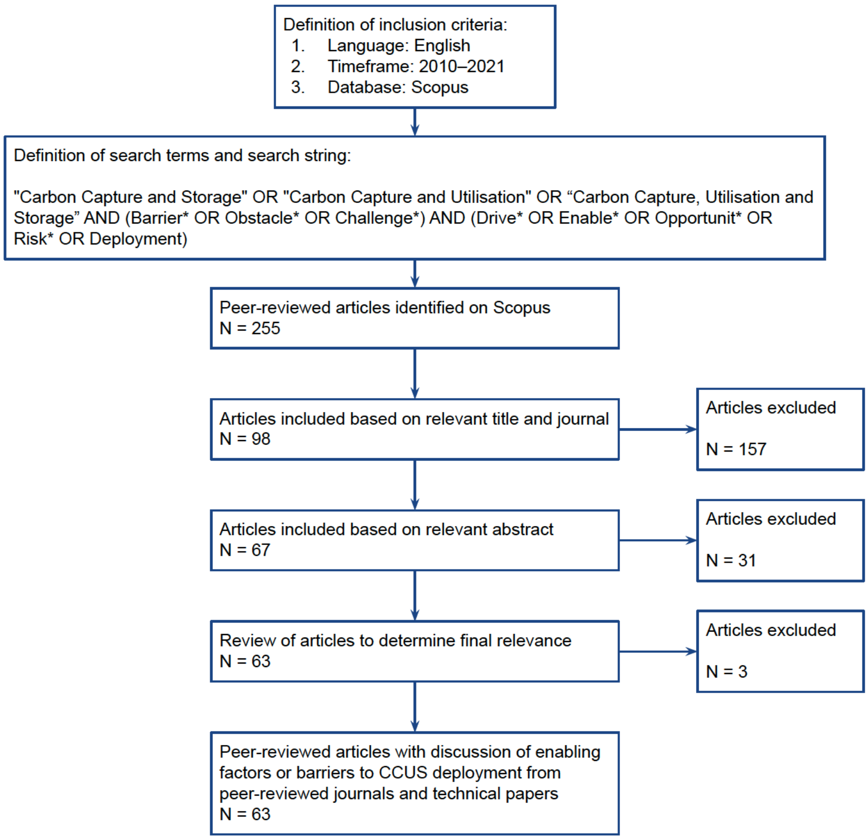

Figure 3.1. Visualisation of decision process for the systematic review of peer-reviewed literature using the Scopus database.

Firstly, the in- or exclusion of each of the 255 articles were determined based on the topic presented in their title, which had the purpose of removing any articles describing unrelated topics (e.g. articles in irrelevant fields of science (e.g. medical science) or highly theoretical engineering process modelling). From assessing the titles, 98 articles were deemed relevant and moved forward to the second assessment, which examined the relevance further by reading the abstracts. Here, articles without a clear interest in the strategic challenges of CCUS project were excluded. The result was 63 articles, including review papers, which were subsequently analysed in detail to determine their relevance and usefulness in building a comprehensive framework of CCUS enablers and barriers.

Identifying factors impacting CCUS deployment

The identification of factors impacting CCUS project feasibility was performed using a four-stage process, beginning with the systematic review of peer-reviewed articles:

1. **Scoping of text**: each article underwent initial scoping by determining sections of relevance from the contents list and by identifying key sub-sections. These were read to identify relevant passages of text, which were subsequently recorded. Next, keyword searches were performed using the search terms described previously, focusing on the words "enable" and "barrier", as well as associated synonyms. This ensured additional relevant passages of text missed in the first iteration were identified.
2. **Keyword identifiers**: after relevant passages of text were identified and recorded, keyword identifiers were applied to help describe the text using a single phrase or word.

For example, a discussion of how subsidies from government could help encourage private investment in CCUS projects was given an identifier of "subsidies".

3. **Categorisation of factors**: next, the full list of keyword identifiers were grouped into broad overarching categories. This was done by first interpreting the overall context of the enabler or barrier described, resulting in an initial grouping of thematically related phrases under defined headings (e.g. "economic"). Variations of phrases with the same inherent meaning were excluded to avoid duplicates e.g. "CO_2 price" and "carbon pricing". Next, an in-depth discussion and analysis was performed for each identifier to unify different terms where the same core issue was being described. This allowed each phrase to be categorised into a more detailed sub-group. For example, the identifiers "NIMBYISM" and "public acceptance" were grouped under the related sub-heading "public perception" (see appendix B).
4. **Definition of factors**: following initial grouping, each sub-heading was discussed in relation to its potential impact on the deployment of CCUS projects. This allowed for incorrectly placed identifiers to be reassigned or removed whilst forming a thorough description of the sub-heading in question. If a tangible impact was described, the sub-heading was redefined as a CCUS feasibility factor. At this stage, the results were supplemented with data from the grey literature review, with any newly identified keyword identifiers or factors added into the classifications.

Grey literature

Through assessing the relevant peer-reviewed articles, it was noted that non-profit organisations (NPOs) and independent institutes play an important role in CCUS discussions via a substantial body of publications focused on policy through to technical feasibility studies. This represents the so called grey literature, a body of knowledge generated through industry and specialised practitioners often published for free outside of commercial publishing entities [Adams et al., 2016]. Grey literature is often seen in emerging fields of study [Jewell, 2018] and so the peer-reviewed literature study was supplemented with grey literature where relevant. This was done by reviewing the reference lists of the 63 peer-reviewed articles to identify key sources of grey literature. For example, Tjernshaugen [2011] describes Bellona as an important *"policy entrepreneur"* in the article "The growth of political support for CO_2 capture and storage in Norway", highlighting the organisations role in CCS debates in Norway throughout the 1990s to early 2000s. From this approach, three organisations were recognised as playing an important role in CCUS discussions: the Global CCS Institute, Zero Emissions Platform and Bellona.

To identify any enablers or barriers missed by the systematic peer-reviewed literature analysis, the publications section of each organisations respective website was assessed. This was done using the following steps:

- Due to the prolific number of publications on both the Global CCS Institute and the Bellona websites, the search was limited to publications from the last five years e.g. 2016–2020.
- Only English language reports were considered.
- Where searching was possible, a combination of search terms used for the peer-reviewed literature process were applied, e.g. "carbon capture and storage", "challenges", "enablers" and "barriers".
- Publication titles were then reviewed along with available abstracts to identify relevant papers for further analysis.

The grey literature review resulted in an additional 24 publications being identified which discussed either enabling factors or barriers to CCUS deployment. In total, five papers from the ZEP were identified, 16 from the Global CCS Institute and three from Bellona.

3.2 Interview

The semi-structured interview represents a key component of the qualitative analysis performed to explore and answer the research question (detailed in section 2.1). The interviews were split into two rounds, with each interview led by a single interviewer using a predetermined set of questions. Interview guides were prepared to help ensure responses from each interview where comparable, serving as a tool for the interviewer to use to steer the conversation 'back on track' if needed. This allowed discussions to lead in new and unconsidered directions, whilst maintaining focus on the research problem under investigation. Lastly, the prepared interview guide ensured that all questions were answered.

The first set of interviews investigated European CCUS practitioners' experiences, exploring the motivations, barriers and enablers for the projects in order to understand key issues impacting their feasibility. The first round interviews were conducted to answer sub-question 2: *"How do European practitioners experience barriers and enablers to CCUS projects?"*. The first part of the interview followed the theoretical approach of grounded theory, remaining exploratory in nature and allowing the interviewee to discuss their experiences without preconceived knowledge. For the second part of the interview, the theoretical framing switched to a knowledge co-creation perspective, with the interviewer presenting the framework findings from the literature review (chapter 4). The co-creation process allowed findings from literature to be verified, falsified or expanded upon through shared insight. Therefore, once the initial exploratory questions had been answered, the interviewer shared an image showing the different factors, grouped into categories, identified through the literature view. The interviewee was asked to reflect and reevaluate their experiences and answers based on the factors presented whilst highlighting any additional experiences or issues not identified in literature. By examining key CCUS feasibility factors from a practitioners perspective, contextual elements unique to the country in question could be explored.

The second round of interviews were designed to compliment the analysis in sub-question 3: *"What are the issues and uncertainties facing CCUS projects in Denmark?"*. In particular, the questions asked were designed to explore several themes which were identified during the interviews with European project practitioner, relating to the feasibility of the technology from a societal perspective. This round of interviews explored the perspectives of different stakeholders so as not to be limited by a project practitioner perspective. The interview guide used for these questions can be found in Appendix C.2.

In chapter 5, the interviewees comprised practitioners from five different CCS and CCUS projects, whilst chapter 6 included interviews with four stakeholders from diverse sectors in Denmark, ensuring an overview of societal perspectives and issues within the Danish context. Because the field of interest is narrow, the amount of relevant stakeholders was limited. A 'snowballing-effect' approach was used, by concluding the interviews asking the interviewees if they had anyone in mind, who could be beneficial for the project to interview. In total, nine interviews were conducted, and table 3.1 presents the interviewees by job title, employer and date of the interview.

Table 3.1. Overview of interviewees by job title and organisation as well as date of interview.

Interviewees overview			
Name	**Job**	**Organisation**	**Date**
Fernanda De Mesquita L. Veloso	Reservoir Geologist	Strategy CCUS	25/3/21
Aslak Viumdal	Senior Advisor, strategy and business development	Gassnova	26/3/21
Mark Driessen	Manager for external affairs	Porthos	01/04/21
Sebastian Bønding Rasmussen	Business developer	AffaldVarme Aarhus	15/4/21
Charlotte Hartley	Engagement Strategist (Regulatory & Policy)	Acorn	22/4/21
Martin Hostrup	Representative of C4 Service Line manager, Biogas	C4	27/4/21
Jacob Zeuthen	Chief Analyst	DCCC (Klimarrådet)	06/5/21
Arne Remmen	Professor, Department of Planning	Aalborg Universitet	07/5/21
Tarjei Haaland	Climate and energy advisor	Greenpeace Nordic/CPH	26/5/21

All interviews were conducted through Microsoft Teams or other virtual communication programs, both due to the ongoing Covid-19 crisis, but also because of the considerable distances between the researchers and many of interviewees. To ensure a 'normal' and comfortable environment for the interviews, the camera was turned on by everyone, and as introduction all participants introduced themselves. All interviews were recorded and transcribed to ensure transparency for the reader. The transcriptions are located in the supplementary appendices.

3.3 Data processing and coding

The data collected through the literature and via interviews was processed, coded and used to investigate the research question. As the predominant theoretical approach of the study is grounded theory, the collected data was interpreted and then coded and categorised based on the insight gained, rather than analysing the data or forcing the results into a preconceived framework [Järvinen and Mik-Meyer, 2017].

The first and second parts of the analysis (chapter 4 and chapter 5) rely on data coded from the literature review, with a systematic approach used in excel to unify and categorise the identified barriers and enabling factors (see section 3.1 for more detail). The coded and categorised results were then presented as a simple framework (table 4.1).

The data collected through interviews was coded using a text and audio analysis tool, Nvivo, which allowed for multiple layers of coding. Firstly, the data was coded based on its category (e.g. social, economic, environmental, organisational, political or technological), which is referred to as top level codes. Secondly, each of the categories were divided into two sub-categories that identified the statement as either being a *barrier* or an *enabler*. Statements coded as *barrier* identified aspects under a specific category as being a barrier to the deployment of CCUS projects, and therefore an issue negatively impacting CCUs feasibility. Exemplified by the interview conducted with Strategy CCUS, the interviewee stated *"I think this kind of reaction would be* *likely if the public is not involved in the project before. We are imposing"* [Strategy CCUS, 2021], which is related to not involving the public in an area that is suitable for geological storage. This was coded as a social barrier to the deployment of CCUS, because the absence of public involvement has the risk of creating public opposition. Conversely, a statement coded as *enabler* highlights a positive feature that has driven, or will drive, the deployment of CCUS forward. For example, in the interview with Gassnova, the interviewee stated *"many of the large analyses on how to reach the climate ambitions like the Paris Agreement for example, they put a very strong emphasis on CCS so it was kind of a situation where everyone saw, in one way or another, that we needed CCS"* [Gassnova, 2021]. This highlights the driving force behind political support, and was coded as being a political enabler.

Once the data from the interviews was coded, Nvivo was used to visualise the results in figures comparing the number of times each category was mentioned during the interview, as well as the relationship between statements relating to barriers and enabling factors (see figure 3.2 below).

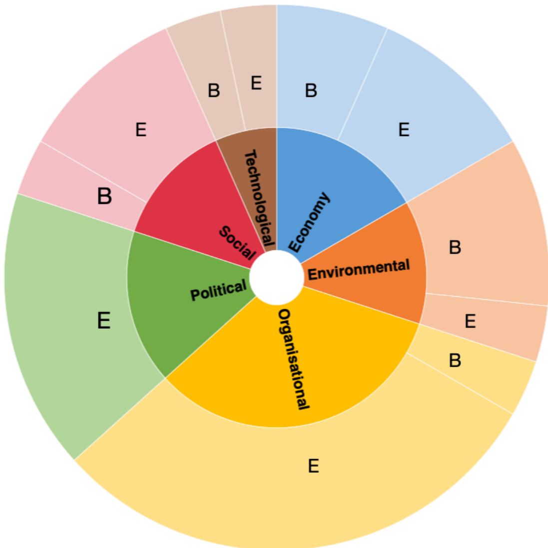

Figure 3.2. Example of a pie chart from data coded using Nvivo, showing the relative proportion with which the six categories were mentioned. Here, the results indicate that organisational enablers (E) were discussed more than barriers (B).

Illustrated in figure 3.2 are results of coded data from the interview with Gassnova. The inner circle shows the categories, and the weight they carry in terms of how many times they were mentioned by the interviewee, whilst the outer circle represents the barriers (illustrated as B) and enablers (illustrated as E) related to each category. The encoded and visualised results of the interviews are used throughout chapter 5 to support the interview analysis by showing the variations that exists in how European practitioners experience different CCUS feasibility factors in different national contexts.

Factors influencing CCUS feasibility 4

This chapter identifies, describes and analyses the factors impacting the feasibility of CCUS projects worldwide based on the results from the literature review (section 4.1). Their interrelationship is discussed, and the results are supplemented with data from grey literature where relevant. The findings represent a mix of both theoretical and experience-based knowledge gained from historic projects across the world.

4.1 Defining a conceptual framework of influencing factors

The results of the literature review are presented in table 4.1 and comprise a list of 20 factors placed into six categories. The categories were defined as relating to social, economic, technological, environmental, political and organisational factors, and are the result of the categorising described in section 3.1. For the comprehensive list of keyword identifiers and groupings behind each category, along with accompanying references, see appendices A and B.

Table 4.1. Conceptual framework of factors which impact the feasibility of deploying CCUS projects, divided into six categories: social; economic; technological; environmental; political; and organisational.

No.	Category	Factor
1	Social: *Societies awareness, perception and acceptance of CCUS as a climate mitigation technology*	**Trust**: between stakeholders and in technology **Public perception**: opinion of CCUS technology **Cultural elements**: tendencies for behaviour and social norms **Knowledge**: of the technology and processes
2	Economic *Factors impacting the economic viability of a CCUS project*	**Financial incentives**: monetary benefit to motivate engagement **Market incentives**: push-pull dynamics from market **Business model**: framework for delivering and capturing value **Cost of technology**: the economic costs of CCUS infrastructure
3	Technological *Technical issues affecting the uptake and dispersal of CCUS technologies*	**Technology readiness level**: maturity of technology **Technology performance**: how efficient a technology is **Infrastructure proximity**: distance of industry to key infrastructure
4	Environmental *How CCUS impacts the environment*	**Mitigation potential**: scale of GHG reduction possible **Environmental risk**: impacts from e.g. leakage
5	Political *Legal instruments and the political setting of the host country*	**Policy**: a principle or stance guiding government **Regulation**: instrument for insuring compliance **Legislative framework**: system of legal documents defining rules **Political support**: degree that government supports something
6	Organisational *Factors facilitating CCUS engagement*	**Coordinating actors**: actors supporting a project or process **Coordinating activities**: actions and motivations supporting a process **Clusters**: geographic concentration of emissions or storage sites

4.1.1 Social

Factors grouped under the 'Social' category were defined as issues relating to society's awareness, perception and acceptance of CCUS as a climate mitigation technology. In total, four social factors were identified consisting of trust, public perception, cultural elements and knowledge (table 4.1).

Trust is defined as trust in CCUS technology and trust in government and in and between organisations. Karimi and Toikka [2018] highlights a lack of trust in CCUS as a climate mitigation strategy in Poland due to concerns over the risks of the technology. Trust in organisations and governments is also found to be an important barrier, with several authors documenting a disparity in the level of trust communities place in local politicians versus organisations working with CCS technology [Löfstedt, 2015; Cherepovitsyn et al., 2020]. Generally, private organisations are seen as less trustworthy than independent and academic sources of information [Cherepovitsyn et al., 2020]. Trust is therefore directly impacted by the *public perception* of the organisations involved [Löfstedt, 2015], a factor which describes the beliefs or opinions of different populations regarding an idea or concept. Offermann-van Heek et al. [2018] build on this by investigating public acceptance of synthesised carbon capture and utilisation (CCU) products, showing that scepticism and the view that CCU is simply delaying the release of CO_2 emissions can lead to a negative perception and a lack of trust in organisation promoting the products.

The results of the literature review also show *knowledge* to be an important factor which directly impacts several of the other factors identified (table 4.1). For example, the level of knowledge that the public have, and how well the risks associated with CCUS technology are understood, are underlying the social issues of trust and public perception [Offermann-van Heek et al., 2018]. Similarly, knowledge sharing is found to be an important factor throughout literature, with multiple studies emphasising the value of knowledge transfer or knowledge diffusion in scaling CCUS projects from demonstration scale up to full commercial entities [van Alphen et al., 2010; Diego et al., 2017]. In this context, knowledge transfer can improve understanding and thereby technology performance, with the communication of risk helping to reduce the cost of technology deployment.

Lastly, *cultural elements* were identified as a critical factor for the deployment of CCUS depending on setting. For example, Datta and Krishnamoorti [2019] showed that the long anti-establishment history in the Assam region in India has often resulted in large infrastructure projects being highly susceptible to negative public perception and a lack of public acceptance which they viewed as problematic for new CCUS initiatives in the region.

4.1.2 Economic

The 'Economic' category was identified as a result of widespread consensus that issues relating to the economic management of CCUS projects are a key influencing factor. Economic concerns are a well documented factor in the emergence of CCUS, being discussed in the majority of the publications analysed (appendix A). The 'Economic' category was categorised by four key factors, namely financial incentives, market incentives, business model and cost of technology (table 4.1).

Financial incentives encompass financial aids from both governmental and private organisations. In the context of governmental organisations, Gunderson et al. [2020] describe government subsidies as a key instrument in maturing the technology, as it will aid in decreasing both capital and operating costs as well as overcoming any technological uncertainties. Additionally, multiple publications identified the importance of government funding in the initial stages of CCUS, because it provides security to private investors and covers any additional costs that companies are unable to recuperate [Stigson et al., 2012; Sara et al., 2015]. Despite the importance of initial government funding in developing CCUS technologies, Bowen [2011] suggests that government funding inevitably will be dwarfed by private investments once CCUS projects are being deployed with commercial feasibility. However, barriers relating to technology (uncertainty and cost) as well as public acceptance are hindering private investments, and will continue to do so if they are not assessed [Bowen, 2011; Rai et al., 2010].

Market incentives comprise measures that seek to incentivise deployment and development of CCUS technologies, but rather than focusing on funding and investments, it describes market mechanisms designed to move CCUS towards economic viability. Assessing the market incentives in the US, Dismukes et al. [2019] describes how the '45Q tax credit' has had a positive impact on the number of CCUS projects by providing a tax benefit to organisations captured CO_2, with permanent storage receiving a higher tax break compared to carbon capture for EOR. In the US, EOR is widely used, providing industrial emitters with a revenue stream to help reduce costs, thereby changing the nature of CO_2 from being a pollutant to a valuable resource [Dismukes et al., 2019]. Viewing captured CO_2 as a resource, creating a market for it and settling on a fixed carbon price are described as mechanisms which would further aid in the deployment of carbon capture technologies, because it would bring in revenue from the capture process and increase the economic viability of projects [Gunderson et al., 2020]. The EU ETS represents another major market incentive driving innovation around decarbonisation projects today. The ETS was the worlds first major carbon market and works through a cap and trade system where sources of emissions use allocated quotas and purchase additional quotas to cover their annual emissions. Over time, the EU has gradually reduced the number of quotas in circulation, leading to an increase in the ETS price designed to encourage industry to decarbonise through innovation [EC, 2003]. Presently, the ETS price is approximately €50/tCO_2, whereas the estimated costs for a full-chain CCS project is around €120/tCO_2 [e.g. Gassnova, 2020], making CCS still less cost effective than purchasing additional quotas. Furthermore, CCU is not currently recognised under the ETS, meaning products synthesised via utilisation still need ETS quotas to cover their emissions, as opposed to CCS where permanently stored emissions do not need accounting for [Schenkel, 2020].

According to Muslemani et al. [2020], one of the most fundamental reasons why CCUS is not an established technology in industrial sectors, is that there is yet to be defined concrete *business models* for the operation of the technology. Clear and concrete business models will eliminate uncertainties surrounding responsibility and reward issues, as well as allocate risks and liabilities [Muslemani et al., 2020]. Furthermore, business models will also accommodate issues relating to cost of technology, which is the most cited issue throughout the literature review (figure 4.1).

The majority of the economic concerns in deploying CCUS projects identified in literature were found to be related to actions that can decrease the capital and operational costs [e.g. Budinis et al., 2018; Pappijn et al., 2020; Rai et al., 2010]. Therefore, the main economic barrier can be summed up as the overall *cost of technology* and operation, and the lack of actions to mitigate this problem.

4.1.3 Technological

Results from the literature review underscore CCUS as a complex and evolving innovation [e.g. Zhang and Huisingh, 2017; Bui et al., 2018]. In total, four factors within the 'Technological' category were identified impacting the feasibility of CCUS deployment, comprising the technology readiness level, technology performance and proximity to existing infrastructure (table 4.1).

Technology readiness level is defined as the degree of maturity a technology has reached and ranges from the initial stages of research through to full deployability. Technology readiness level was discussed in various contexts, from carbon capture technologies to synthesising products via CO_2 utilisation [Diego et al., 2017; D.N.Kamkeng et al., 2021]. For example, carbon capture technology is commercially mature, with MEA capture systems either operational or being implemented in several full-scale initiatives worldwide. These include the Boundary Dam project in Canada [Diego et al., 2017], the Shengli CCS project in China [Zou and Zhang, 2017] and the Norwegian Longship project [Lipponen et al., 2017]. However, alternative capture technologies such as oxy-fuel systems offer higher capture efficiencies with much lower levels of energy consumption [Nuortimo et al., 2018], a potentially critical factor for manufacturing industries such as the cement industry, where excess heat to power carbon capture is not available [Bui et al., 2018]. However, presently oxy-fuel capture remains noncommercial and limited to demonstration projects due to higher capital expenditure requirements [Bui et al., 2018; Nuortimo et al., 2018].

Technology performance was identified as a key factor impacting operating efficiency throughout the CCUS value-chain. For example, liquefaction — the process where CO_2 is compressed into a liquid to ensure safe transportation — is an energy-intensive process requiring access to sufficient sources of renewable energy in order to reduce life-cycle emissions [Bui et al., 2018]. Performance issues were also well documented in the grey literature. For example, the Global CCS Institute [2020a] discuss how carbon capture costs rise as the purity and concentration of CO_2 in industrial flue gases fall due to the efficiency of the solvents used in MEA capture systems. Low concentration CO_2 streams are common in fossil-based power generating industries such as coal and natural gas fired power stations, with the Global CCS Institute [2020a] concluding that capture costs from gas power plants can cost twice as much as CO_2 captured from coal.

Lastly, *infrastructure proximity* was described as an important enabler for CCU and CCS projects. This factor includes access to geological storage and access to infrastructure, such as pipelines. For example, Zou and Zhang [2017] discusses how the uneven distribution of geological storage sites across the world is likely to impact the roll-out of CCS in certain countries, highlighting China's well classified storage capacity as driving national interest. Access to geological storage was also discussed in grey literature, where it is viewed as key to minimising transport distances and thereby costs [e.g. Global CCS Institute, 2016b; ZEP, 2019]. The Global CCS Institute [2016b] further describe how research into geological storage sites can give proof of concept to emerging national CCS initiatives, showing how advanced storage capacity assessments in the US, Canada and Norway have helped accelerate CCS deployment.

4.1.4 Environmental

CCUS is increasingly viewed as an emissions reducing technology and an essential component in the path toward net-zero emissions (chapter 1). However, as discussed in section 4.1.3, CCUS is also an energy-intensive process which carries with it associated life-cycle emissions [Bui et al., 2018]. The mitigation potential of the technology is therefore identified as an important factor influencing the rationale for CCUS deployment worldwide. In addition, environmental risk is widely discussed as a factor which has the potential to delay CCUS projects whilst significantly impacting public perception (section 4.1.1). These were grouped under the 'Environmental' category.

Mitigation potential describes the reduction in harmful emissions that carbon capture, transport, utilisation and storage can deliver when applied to industrial sources of CO_2 [Chaudhrya et al., 2013; ZEP, 2020]. The potential for CCS to reduce emissions from hard-to-abate industries is significant, with the decarbonisation of sectors such as the cement, steel and iron industries only deemed possible with the help of the technology [Bui et al., 2018]. However, its true mitigation potential is determined by numerous factors such as the efficiency of the capture technology used (e.g. section 4.1.3), life-cycle emissions throughout the value-chain and whether CO_2 is stored in a geological site or utilised in synthetic products (termed the retention time) — utilising CO_2 in processes such as e-fuels only retains the emissions for a relatively short period of time [ZEP, 2020], Furthermore, due to the laws of thermodynamics, CCS cannot operate in an energy-neutral environment as significant heat and electricity are needed for both capturing and compressing CO_2 [ZEP, 2020]. The net mitigation potential therefore depends on the source of electrical energy, the availability of surplus heat and the end use, or destination, of the CO_2. Ultimately, without access to renewable energy sources, life-cycle emissions will be higher and the mitigation potential reduced [Stuardi et al., 2019; ZEP, 2020]. This is further compounded in CCU technologies, where larger quantities of renewable energy are also required [e.g. Pappijn et al., 2020].

The second environmental factor identified relates to *environmental risk* and was dominated by discussions on the risks of CO_2 leakage. The environmental risk of CO_2 leakage is described in two specific context, (1) the risk to human health following a leak from either a pipeline or storage site [Liu et al., 2016; Leiss and Krewski, 2019] and (2) the risk of a geological storage site failing and leaking CO_2 back to the atmosphere [Harding et al., 2018]. Liu et al. [2016] discuss the risks associated with CO_2 leakages and identify potential loss of life, contamination of groundwater and soil contamination as significant impacts. These risks — whilst in theory easily avoided providing adequate monitoring practises are in place — play into the decision-making process and are often at the centre of negative public perception [Stigson et al., 2012; Liu et al., 2016] and concerns over economic liability [e.g. Sara et al., 2015]. Lastly, Harding et al. [2018] describe the significance of a storage site failure occurring and show that when even 0.1% of injected CO_2 leaks from a storage site, then approximately 90% of the total injected volume could be lost in just 2000 years.

4.1.5 Political

Factors grouped under the 'Political' category were identified as relating to legal instruments or the political setting of the country in question. In total, four factors were identified, comprising the policy framework, legislative framework, regulation and the political support given to CCUS (table 4.1).

Policy refers to specific actions or statements by a government organisation which sets out a deliberate system of rules or principles made to guide and achieve goals. Policy is widely discussed in peer-reviewed and grey literature in the context of CCUS, with both weak policy and policy uncertainty shown to be a major influencing factor in its deployment on a national level [e.g.

Diego et al., 2017; Zhang and Huisingh, 2017; Budinis et al., 2018; Gunderson et al., 2020]. For example, Budinis et al. [2018] discusses the need for stronger climate policy and policies focusing specifically on carbon taxes and carbon trading mechanisms. Without concerted global efforts to create a market for CO_2, Budinis et al. [2018] concludes that CCS will not be deployed to a sufficient enough level for climate change to be avoided. The current lack of policy aimed at creating such a market is also identified by the Global CCS Institute [2020a], who see it as representing a major barrier to the further deployment of CCUS worldwide. The Global CCS Institute [2018a] further correlate Norway's long history of policy favourable to CCS as being directly responsible for its position as Europe's front-runner in CCS (for more detail see chapter 1 and section 5.1).

The factors *legislative framework* and *regulation* are closely related, with legislation setting out the law in the form of rules which must be followed. Regulation supports the legislative framework by setting out details regarding how legislation is enforced with action. A central piece of European legislation is the CCS Directive (Directive 2009/31/EC) which was the first of its kind to provide a legal framework for the safe geological storage of CO_2 [ZEP, 2019]. Heffron et al. [2018] discusses how different EU member states have transposed the 'CCS Directive' differently, meaning that some legal uncertainty persists regarding issues such as liabilities and the trans-boundary movement of CO_2. This raises issues relating to inconsistencies between regionally versus internationally consistent approaches to regulation. For a country outside of the European parliament, the problem is another. China is not starting with a blank slate when it comes to CCS regulation, therefore an initial challenge is to either draft a new law under which CCS will fall or rewrite the existing ones to better encompass CCS [Zou and Zhang, 2017]. A problem which is also related to countries in Europe, with offshore CO_2 storage and utilisation for CO_2-EOR likely being governed by different regulatory frameworks. Regulatory regimes for storage offshore and onshore utilisation already exist, but offshore utilisation (CO_2-EOR) is likely to be governed by regulations for oil, gas, and petroleum [Eide et al., 2019].

Political support is argued to be a critical factor in the deployment of CCUS. The literature review shows that a strong political support system can influence a wide range of factors such as motivation, ambition, pro-activity, and engagement. All factors depend on how the political support is received and interpreted by the industries and the public [Bowen, 2011; Bui et al., 2018]. Political support is often seen as the role of the government in improving business cases for CCS and guaranteed governmental support in the long-term. Furthermore, it is stated that without it, it is unlikely that CCS will be deployed properly [Sara et al., 2015; Bui et al., 2018]. Tjernshaugen [2011] expresses that governments, across borders, experience increasingly, politically dilemmas concerning climate- and energy policy that have impacted that political support concerning CCUS is difficult to gain. Political support is caused by positive feedback when introducing arrangements that help strengthen actors or promote innovation [Tjernshaugen, 2011]. All elements which Norway has done to reinforce the political support for the energy- and climate-policies in question and what Tjernshaugen [2011] sees as a solution to get political support in other countries.

4.1.6 Organisational

The factors relating to the 'Organisational' category describe a range of elements including internal and external collaboration, various management best-practises and actors who facilitate and influence CCUS project development. In total, three factors were identified comprising coordinating actors, coordinating activities and the presence of clusters (table 4.1).

Coordinating actors refers to the range of actors who influence CCUS project planning and public debate, with the results of the literature review showing the important role that actors of different compositions (e.g. industry, research institutes or public authorities) can have on the deployment of CCUS [e.g. Widjanarko and Ubaydullaev, 2011; Tjernshaugen, 2011; Bui et al., 2018]. For example, Bowen [2011] recognises the important role that corporate decision-making plays in advancing the case for CCUS deployment, highlighting how adopting CCS as a key strategy remains problematic due the lack of financial benefits. This is compounded by the a tendency to view climate change as an intangible and distant problem, meaning that many organisations continue to engage with CCUS only where its deployment is aligned with other organisational objectives [Bowen, 2011]. The historical context of CCS in Norway was assessed by Tjernshaugen [2011] who identified the central role that NPOs and the Norwegian Climate and Pollution Council played in promoting CCS technology throughout the 1990's and early 2000's. In particular, the Bellona Foundation emerged as a strong proponent of CCS technology, helping to tip the political balance toward the Socialist Left Party in 2007 and therefore in favour of CCS as an emissions reduction strategy [Tjernshaugen, 2011]. Another key aspect of coordinating actors relates to the role of regional, national or international development organisations which act as coordinators for CCUS projects. Heffron et al. [2018] describe the need for such organisations in order to minimize legal hurdles and improve project management efficiency [Heffron et al., 2018], whilst the ZEP [2016] suggest the lack of such organisations is to blame for the delayed national interest seen in countries like Poland and Spain. Edwards and Celia [2018] further highlight the need for close coordination between major project stakeholders, in order to avoid a situation where expensive capture technology is installed without access to existing capacity for transportation or storage, or visa-versa.

The second factor described under the organisational category refers to coordinating activities, determined here as issues related to the strategic dimension of planning. Another important issue falling under the coordinating activities factor relates to an organisations existing technological profile, its expectations and motivations for engaging with CCUS. Bowen [2011] describes how these are typically misaligned with the external environment, with managers of industry and energy companies often ill-equipped to tackle the diversity of issues facing CCUS projects. To overcome these issues, Stigson et al. [2012] recognises the need for a dynamic and flexible approach in order to adjust the project as and when future demands and needs change. This leads into the conclusion of Gough et al. [2010], who identify the need for broad knowledge and a holistic overview of the CCUS value-chain network in order to ensure that environmental impacts are minimised.

The third technological factor identified relates to emissions and storage clusters (often termed hubs). Emissions clusters refers to a geographic concentration of CO_2 emissions, whilst storage clusters refers to a concentration of geological storage sites in relative proximity. Clusters are important in allowing organisations to pool resources and develop shared infrastructure solutions, thereby helping to minimise cost through economies of scale, spread risk and reduce liabilities in the event of system failure [ZEP, 2016; Heffron et al., 2018]. Emissions clusters are also important for encouraging smaller sources of emissions to deploy carbon capture technology Bui et al. [2018]. Both emissions clusters and storage clusters feature prominently in the grey literature [e.g. Global CCS Institute, 2016a; ZEP, 2016; Global CCS Institute, 2020b], where they are seen as essential key for reducing costs and spreading risk. Similarly, storage clusters are also described as an important enabling factor, with sufficient nearby geological storage allowing projects to be scaled and prolonged, again helping to reduce costs [Global CCS Institute, 2016a].

4.2 Summary of factors influencing CCUS deployment

The results of the literature review identified 20 factors impacting the feasibility of CCUS deployment globally and were based on academic literature from the last 10 years. Data from grey literature was used to supplement the analysis, after which the results were grouped into six categories (table 4.1). The results highlighted a focus on the economic, political, and social dimensions and show that the 20 identified factors are interrelated.

Factors grouped under the economic category were the most represented and were discussed in the majority of the peer-reviewed articles analysed. Of the 20 factors identified, cost of technology was the most widely presented, appearing in 20 of the 63 articles assessed, whilst financial incentives were discussed in 19 separate articles (figure 4.1). The prevalence of these two factors underscores how uncertainty regarding who should fund CCUS, and how, remains an key concern today [e.g. Budinis et al., 2018]. Economic concerns were also discussed in the grey literature, with a focus on the importance of market instruments, specifically CO_2 pricing [e.g. ZEP, 2019; Global CCS Institute, 2019, 2020b], in incentivising new CCUS projects.

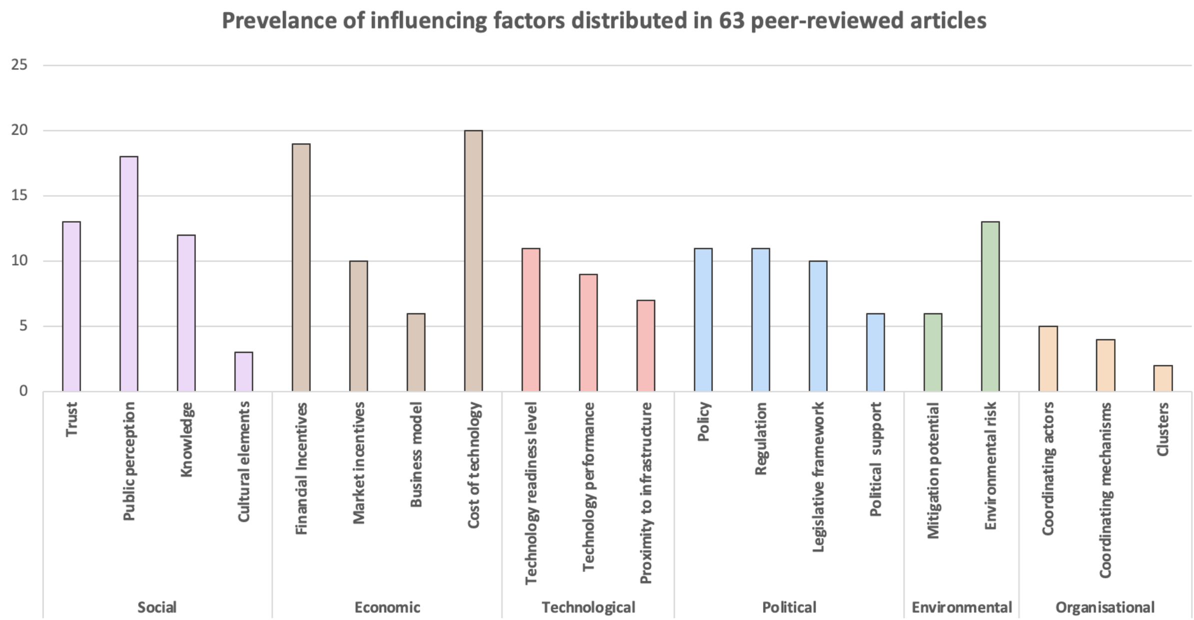

Figure 4.1. Summary of factors influencing CCUS deployment and their prevalence in the 63 peer-reviewed articles analysed.

Social and political factors also featured prominently and were documented in 48% and 43% of peer-reviewed articles, respectively. In particular, public perception emerged as an important factor influencing the support for CCUS projects and was shown to be closely related to trust in governments and organisations, as well as knowledge [e.g. Offermann-van Heek et al., 2018]. Social factors were poorly represented in grey literature and discussed only in relation to social cost-benefit analyses [Global CCS Institute, 2018b]. This is put down to the nature of the research organisations working with CCUS today, who typically act as technical advisors to larger institutions (e.g. the Zero Emissions Platform). Conversely, political factors were a key theme in both peer-reviewed and grey literature, as seen in Norway where strong political support and the development of a clear legislative framework are seen as having played a central role in making the deployment of CCUS feasible [e.g. Heffron et al., 2018; Karimi and Toikka, 2018].

Technological factors were also well represented and discussed in 31% of peer-reviewed articles. The most prominent technological factor identified was technology readiness level. In particular, the literature indicates that it is the maturity of utilisation technologies, rather than capture systems, which remains the technological barrier today, with the cost of catalysts combined with large energy requirements impacting technology performance which makes utilisation presently noncommercial [Pappijn et al., 2020].

Of the six categories defined, organisational and environmental were the least widely discussed within peer-reviewed publications (figure 4.1) and were also largely absent from from grey literature. The discussions presented on environmental risk remained focused on CO_2 leakage [e.g. Leiss and Krewski, 2019] and were often contextualised in relation to negative public perception [Offermann-van Heek et al., 2018] and concerns regarding financial liabilities [Muslemani et al., 2020]. The mitigation potential of CCUS was also discussed [Gunderson et al., 2020] due to concerns regarding life-cycle emissions throughout the value-chain.

Despite the narrow focus of grey literature compared to peer-reviewed resources, the grey literature was instrumental in identifying clusters [e.g. ZEP, 2016] as an influencing factors. Furthermore, grey literature was also important in contextualising the 20 key factors identified with respect to active CCUS projects and current legislative frameworks [e.g. Global CCS Institute, 2019], with projects such as Norway's Longship initiative also only being discussed in grey literature [Global CCS Institute, 2018a]. This underscores the importance of incorporating grey literature and the perspective of present CCUS practitioners and highlights the more reflective nature of peer-reviewed articles.

CCUS experiences from European practitioners 5

This chapter explores how the framework of factors identified in chapter 4 have impacted active CCUS projects in Europe. By interviewing practitioners working in the field of CCUS today, the importance of national setting, and the way practitioners experience different feasibility issues, is explored. The results are used to expand the framework and to develop new knowledge of contextual barriers and enabling factors impacting CCUS feasibility. The results are explored for each project individually before concluding with a short summary of the key findings and important comparison points.

Figure 5.1 shows the location of the five European CCUS projects interviewed. Longship, Porthos and Acorn represent projects in active planning or development, with a combined 8.3–9.3 Mta of CO_2 emissions reduction targeted, the C4 project is in the concept stage and targets 3 Mta of CO_2, and Strategy CCUS represents an early-stage feasibility project with mitigation potential currently uncertain.

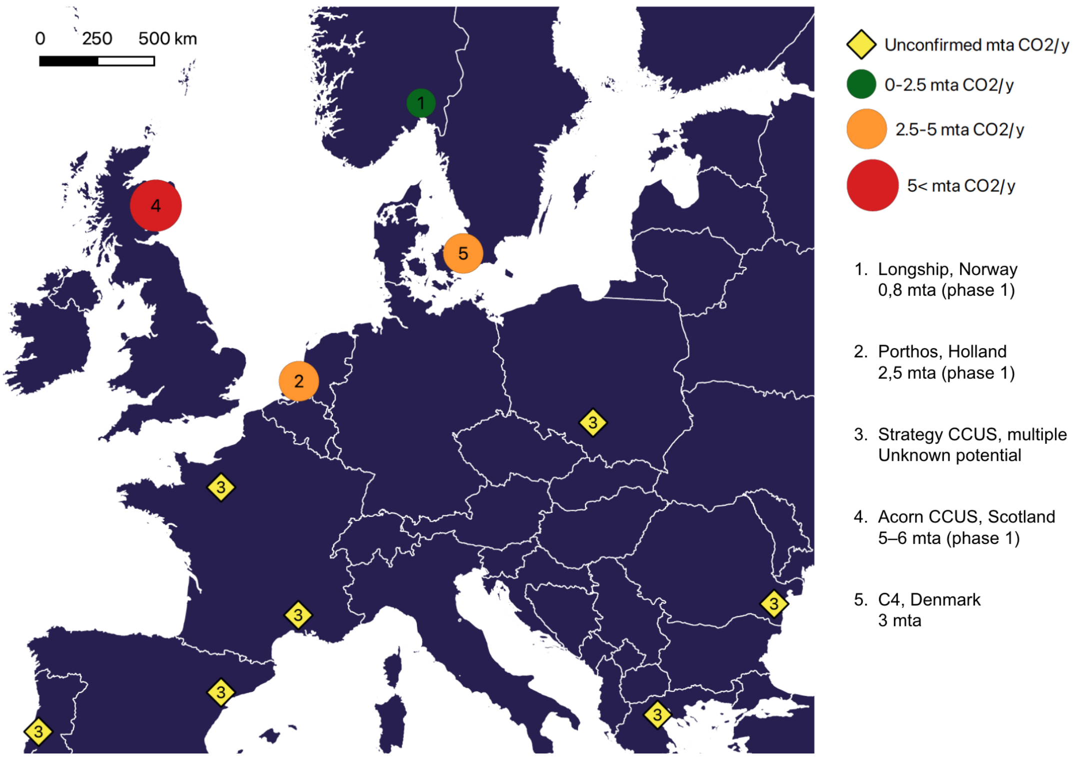

Figure 5.1. Location map of the European CCUS projects interviewed, showing relative size of emissions (Mta) being targeted for capture, where known.

5.1 Longship (Gassnova)

Longship is Europe's most advanced climate-focused CCS project and has been under consideration and planning since at least 2015. The project is managed in a public-private partnership, with Gassnova — a state-owed enterprise — coordinating between private industry on both the capture side as well as for transportation and storage. In 2020, the Norwegian parliament approved € 1.7 billion in funding for the project, with construction now underway [Norwegian Ministry of Petroleum and Energy, 2020]. In its first phase, Longship will capture 800.000 tCO_2/y from both a cement factory and from a waste-to-energy plant near Oslo, before transporting the CO_2 by ship to a distribution hub north of Bergen for onward transportation via pipeline to an offshore storage site [Gassnova, 2020].

5.1.1 Motivations for the project

Two key motivations behind the Longship project emerged from the interview. Underpinning the initiative, is a widespread view that CCS is a necessary technology for combating climate change. For example, [Gassnova, 2021] stated that *"many of the large analyses on how to reach the climate ambitions like the Paris Agreement [...] put a very strong emphasis on CCS"*. This ties back to the assessments from the IPCC [2018], where CCS is cited as an essential technology. However, Gassnova also highlight that a driving consideration throughout the Longship project has been to demonstrate CCS as a functioning climate mitigation solution, using the Longship project to *"show that the whole chain can function both regulatorily, technically and commercially"* [Gassnova, 2021]. Norway is interesting in that Longship is not the nations first CCS project, with geological storage of CO_2 separated from natural gas occurring since 1996 at the Sleipner Field [Lipponen et al., 2017]. Norway's economy is also largely built around the offshore oil and gas industry, which in Norway is perceived positively due to the employment opportunities and economic security it provides. This means public support around CCS is high [Gassnova, 2021]. Gassnova also recognised the impact of its offshore industry in driving global warming and climate change [Lipponen et al., 2017]. This history is important in contextualising Norway's sustained political support for CCS and why Norway has been funding CCS research since the early 2000s [AirClim, 2015]: *"almost all politicians and all parties agree that CCS is a solution that Norway should spend money on"* [Gassnova, 2021].

Ultimately, Longship is seen as a way of moving past the economic and regulatory stalemate often seen with CCS projects and for pushing the technology and knowledge around CCS forward in an attempt to: *"break out of a circle of inaction"* [Gassnova, 2021].

5.1.2 The importance of context: the coordinator

A key theme to emerge from the interview with Gassnova relates to the need for a coordinating body to manage CCUS projects. This has been concluded in an early stage pre-feasibility study, which recommends dividing state-owed activities into two distinct value-chain components — the capture site as one entity and the transport and storage as another. This decision is seen as highly important for the project, with Gassnova given the *"project integrator role"* [Gassnova, 2021]. This role involved *"trying to integrate the different industrial parties"* and *"working in the interfaces between the involved parties"*. For Gassnova, this also meant coordinating assessments during the planning stages [Gassnova, 2020] and getting the key industry and government stakeholders talking to each other, a process recognised as key to building trust between organisations and actors [Tjernshaugen, 2011]. Gassnova [2021] elaborates: *"I am not* *sure we could have had [a] positive investment decision without this trust-building process".* This positive dialogue and a commitment on investment also meant that the project quickly moved away from common 'chicken and egg' issues often cited in other CCUS projects [e.g. Porthos, 2021b] — an issue recognised by Gassnova as a major barrier to CCUS advancement. In essence, the issue where industrial emitters sit *"on the fence waiting to see what happens"* [Gassnova, 2021] was overcome by having a coordinator build trust amongst the stakeholders around a shared vision.

5.1.3 Willingness and the business case

The willingness of industry was highlighted as an important factor, with Gassnova [2021] stating that *"one of the biggest issues has been to get the industrial parties involved".* Willingness is shown to be interrelated to several other factors, depending on the industrial actor. For example, willingness from industrial emissions sources is impacted by the need to engage with radically new technologies to those of their core business. Gassnova [2021] explains:*"a cement producer is very focused on being a good cement producer[...] but they are not experts on either building nor running CO_2 capture plants".* This supports the fact that willingness to engage with CCUS is impacted by a company's technological profile (e.g. coordinating mechanisms; section 4.1.6). This was also recognised from oil and gas companies whose interests are aligned with: *"being a storage provider but also seeing the link to their main product [...] the blue hydrogen agenda"* [Gassnova, 2021].

A key factor impacting overall project feasibility and underlying industrial willingness is also the support Gassnova provided in developing a workable business model. This was needed to gather support around the project and gain commitment from the different stakeholders. Gassnova [2021] elaborates that *"no industrial company will be motivated to just cover cost, they will need to have some profit [...] to see this as an interesting part of their business development plan".* This is where Gassnova see the importance of a coordinated "national agenda" for CCUS and the need for strong political support in terms of market regulation and clarity on property rights [Gassnova, 2021]. For example, *"Gassnova will not own anything"* in the Longship project but *"the state needs to be willing to get into a process that will be quite costly"* [Gassnova, 2021]. Overall, the business model was seen as an important driver for industrial motivation.

Figure 5.2 provides an indication of the most influential factors Gassnova encountered in their experience with carbon capture, showing much emphasis on the organisational factor with an inclination towards it being an enabling factor. This is largely be attributed to the fact that Gassnova acts as the facilitator for CCS in Norway, and that fact that they have succeeded in creating an environment of trust and positive perceptions. Additionally, the Norwegian government has been largely supportive of CCS initiatives which is why the political factor was only discussed as being an enabler. The least important factors in the Norwegian context were the social factors, which is, as mentioned, because of the general prosperity of the nations work with offshore oil and gas [Gassnova, 2021].

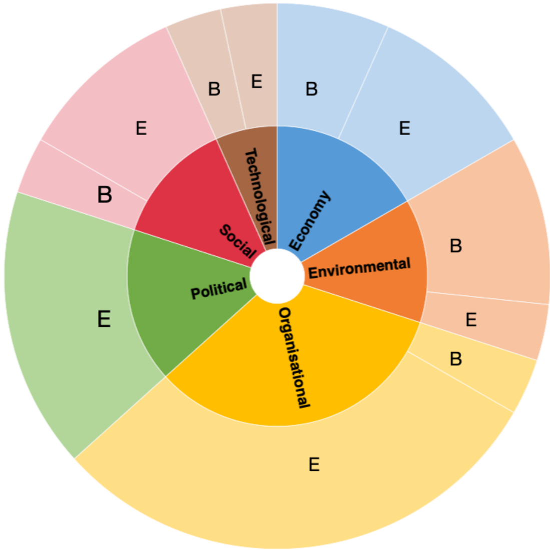

Figure 5.2. Pie chart illustration providing an indication of the barriers (B) and enablers (E) described during interview with Gassnova.

5.2 Porthos

The Porthos project is a CCUS initiative focusing on reducing emissions from heavy industry in the Port of Rotterdam in the Netherlands. The port area represents the largest in the EU and is a predominantly fossil fuel-based industrial cluster, accounting for 17% of annual Dutch CO_2 emissions [Porthos, 2021b]. The Porthos project aims to capture, transport via pipeline, then permanently store 2,5 Mta of CO_2 in depleted offshore gas fields in the Southern North Sea, with a final investment decision expected in 2022 [Porthos, 2021a]. All emissions sources are currently from hydrocarbon refineries in the port area.

5.2.1 Motivations for the project

In 2017, the Port of Rotterdam initiated a joint research project with the German Wuppertal Institute to investigate a road-map for decarbonisation. The results show the Paris Agreement to be an early motivation behind this initiative, with the CEO of the port authority recognising the importance of reducing emissions in the area, if the Netherlands were to meet their nationally determined contributions [Porthos, 2021b]. The Wuppertal Institute report concluded that a 95% decarbonisation would be possible only with the inclusion of CCS technology [Porthos, 2021b], thereby representing a major impetus for initiating the Porthos project. The outstanding global carbon budget — the point above which increased emissions are likely to lead to warming beyond 2°C — is also described as a motivating factor, with CCS being described as *"one of the only technologies that can do such big reductions in such [a] short term"* [Porthos, 2021b]. The interview also highlightd a *"moral obligation"* from the Port of Rotterdam CEO, who is seen as having been central to the initial engagement between the port and the various industrial actors within the port area [Porthos, 2021b]. Overall, the motivations behind the Porthos project were shown to relate to national and international climate policy and the mitigation potential of CCS, with the Port of Rotterdam CEO representing a coordinating actor working with coordinating mechanisms in support of the technology [e.g. Bowen, 2011] (section 4.1.6).

5.2.2 The importance of context: national support

Public perception and political support were both identified by Porthos as crucial in shaping the debate around CCUS in the Netherlands and getting the project off the ground [Porthos, 2021b]. For example, previous experiences from the onshore Barendrecht CCS project resulted in intense opposition from local communities and the project being cancelled by government in 2010 [Bellona, 2010]. The reason being largely due to the perceived negative impact the project would have on house prices in the local area [Bellona, 2010] — on a practical level, Porthos note the lack of people living in the port area as helping to minimise local public opposition [Porthos, 2021b]. However, Porthos discussed the need *"to change the perception of CCS in the Netherlands"* because public opposition has ultimately been *"translated into political opposition"* [Porthos, 2021b]. However, a lack of knowledge regarding CCUS was *"not the main factor"* contributing to negative public perception today, but rather trust and a negative view of large industry is to blame: *"industry in the Netherlands doesn't have a lot of support at the moment. Even politically"*. This scepticism emerged recently following a request from the industrial partners in Porthos (Shell, Exxon, Air Liquide and Air Products) for €2.1 billion in state subsidies, a request which led to *"outrage"* from the public who felt it unreasonable that the polluters would now be compensated for their emissions [Porthos, 2021b]. Today, there is a broader debate around the role of heavy industry in global warming and around who shall pay for decarbonisation [e.g. EEA, 2020], a debate that Porthos [2021b] see as *"one of the big risks of the project, because that sentiment is getting stronger and stronger"*.

In order to shift the debate and build support for the project, Porthos [2021b] highlighted that there has been a huge amount of engagement with politicians across the political spectrum: *"the biggest breakthrough there for us was getting the green party in the Netherlands to support us and [...] express the necessity of Porthos in the parliament"* [Porthos, 2021b]. Efforts were also made to improve engagement with non-governmental organisations (NGOs), including the national Greenpeace organisation, previously a critic of CCUS but who ultimately chose to refocus their criticisms: *"I think we managed so far to convince the others [NGOs] to pick another fight"*.

5.2.3 Willingness and the business case

Porthos [2021b] stated that the single most important factor helping advance the Porthos project are the revisions to 'SDE++ subsidy scheme' [Porthos, 2021b], an expanded financial incentive scheme allocating subsidies toward new technologies and infrastructure aiding in decarbonisation outside of renewable energy [Government of Netherlands, 2019]. This scheme seeks to fill the gap between the cost of CCUS and the ETS, with Porthos [2021b] stating that this *"really is the most important factor because it is always about money"*. Another factor identified in the interview is the role that public organisations played by taking ownership of the transportation infrastructure. CCUS projects have often been stymied by a 'chicken and egg paradox', where a lack of coordination leaves potential capture projects concerned over access to transport mechanisms whilst suppliers of transport value-chains are uncertain over eventual demand [Edwards and Celia, 2018]. This leaves a situation where neither emitter or transport provider commit to a project until assurances are in place. In Porthos, three state-owned organisations took charge of CO_2 transportation planning, seeing strong coordination and a 'cluster' approach as essential for gathering industrial support. For example, *"Shell wasn't willing to take the risk of building a very big infrastructure and letting the other industrial clients make use of it"*, leaving Porthos to conclude that *"you need somebody to coordinate"*. In conclusion, economic factors around CCS emerged as critical: *"you can talk for ages about all the other factors, but the main factor is the business case."* [Porthos, 2021b].

Figure 5.3 provides an indication of the most influential factors the Porthos project encountered in their experience with carbon capture, and conversely to the Norwegian experiences, the social factor is represented a lot throughout the interview. This is a result of the discussion around the negative perception of CCUS in the Netherlands, which, as mentioned, has evolved into political opposition. Furthermore, the organisational factor is represented in figure 5.3 as leaning towards predominantly being a barrier, which is due to the 'chicken and egg-paradox'.

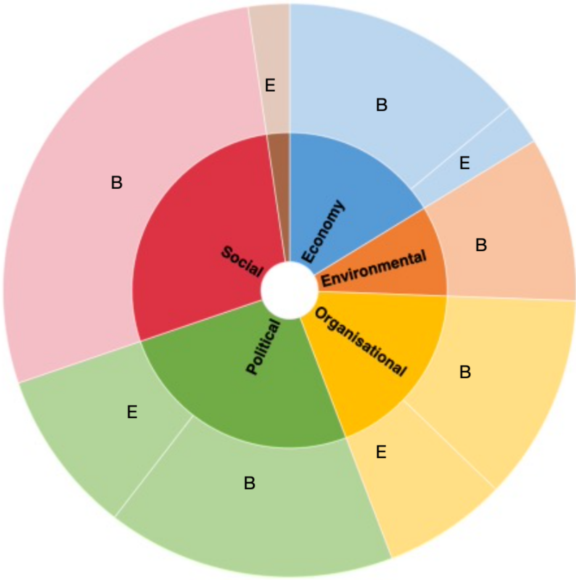

Figure 5.3. Pie chart illustration providing an indication of the barriers (B) and enablers (E) described during interview with Porthos.

5.3 Strategy CCUS

The Strategy CCUS project started in 2019 with funding from the European Union and is expected to run until 2022. Strategy CCUS is a cross-border CCUS project facilitator focusing on reducing emissions in eight different regions in the southern and eastern parts of Europe. Despite the widely spread locations, Strategy CCUS is collaborating with stakeholders in each region to ensure a positive attitude towards the project, as well as a developing the technology to fit the specific context of each region [Strategy CCUS, 2021]. The mitigation potential of CCUS currently remains unclear, with a screening of emissions ongoing. However, a range of heavy process industries and energy plants are under consideration.

5.3.1 Motivations for the project

The motivation behind the initiation of the Strategy CCUS project is based on the assumption, and the experiences, that the capital and operational costs is often the fist topic of discussion in the early development stages of CCUS projects: *"the first question is usually 'how much does CCUS cost?'"* [Strategy CCUS, 2021]. Therefore, Strategy CCUS described their purpose as being able to have an informed discussion based on financial and environmental calculations rooted in reality rather than fictional assumptions — albeit some uncertainties still exists

[Strategy CCUS, 2021]. In this way, the organisation is creating knowledge for different industrial regions across Europe and facilitating research into CCUS as an industrial strategy. The fact that Strategy CCUS is an internationally focused facilitator in eight European regions is reflected in the discussion throughout the interview being more generic compared to Gassnova, Porthos and Acorn. This did, however, not diminish the value of the answers given by Strategy CCUS. On the contrary, it validated an important fact — that the context in which these projects are deployed plays an important role in how the deployment should be handled. Which is why Strategy CCUS is working closely with local government, industry, the general public and other stakeholders across each regions [Strategy CCUS, 2021].

5.3.2 The importance of context: geography, emissions sources and public perception

Strategy CCUS [2021] underscored the importance of regional and national contexts by acknowledging that *"We have eight [very different] regions in terms of kinds of industry, kinds of clusters that can be built, storage, maturity and confidence, and transport infrastructure"*. In particular, Strategy CCUS [2021] emphasise the need to assess each region individually in order to map proximity between emissions sources and their proximity to suitable storage locations and CO_2 transportation (e.g. infrastructure proximity). Furthermore, Strategy CCUS touched upon the important subject of industrial context issues, stating: *"My feeling is that regions that are dealing with emissions from industrial processes are more likely to have CCUS implemented early [...] and for some regions, emissions from energy is not a big challenge"* [Strategy CCUS, 2021]. In this statement, Strategy CCUS drew a distinction between certain types of industries and highlights the importance of considering technology lock-ins. For example, Strategy CCUS [2021] state that: *"energy is not a big challenge, because in time they will change the energy production [...] into renewable energy"*. This statement is grounded in the fact that the high cost of CCUS demands an emission source for a number of decades to ensure economic feasibility, yet the renewable energy transition brings other sustainable alternatives with lower emissions reductions from the sector making CCUS from energy unsuitable in the long term. Strategy CCUS [2021] add that *"The real problem is the industry where the emissions are related to the processing [...] like cement-plant or chemical industry, or even the energy from [waste incineration]"*.

The political and societal contexts of the region in question also have the potential to significantly impact the success of CCUS projects, with [Strategy CCUS, 2021] stating that *"In Germany they stopped some projects with carbon storage because they had societal movements against the project [...] today it is illegal to store CO_2 [in Germany] I think"*. Social acceptance was also described, with much of the identified skepticism relating to the costs of CCUS. Interestingly, this did not seem to vary from region to region, with [Strategy CCUS, 2021] highlighting projects with different stakeholders in *"each region to see the needs and concerns about the technology, and the feeling is people are not against it, but they are very skeptical about economics and cost"*. Conversely, the interview with Gassnova revealed that there had been little public and political opposition in Norway in relation to the cost and general economy of their CCS projects [Gassnova, 2021].

5.3.3 Willingness and the business case

As identified through literature and the interviews with European practitioners, political support is an important factor which governs the overall feasibility of implementing CCUS, an argument also acknowledged by Strategy CCUS [2021]. However, they believe that, in France, it is the industry that is putting pressure on the government to consider the technology as a solution for emissions reduction [Strategy CCUS, 2021]. In the experience of Strategy CCUS, industrial willingness and motivation for CCUS was seen as being at an all time high, so *"if the technology is not able to be developed and deployed now, it will probably never be"* [Strategy CCUS, 2021].

In relation to the expensiveness of CCUS, *"I think, in the world today, money is not a problem if you can prove the environmental benefit will be greater than the money"* [Strategy CCUS, 2021]. However, by using the example of how quickly the world adapted to having to test citizens for Covid-19 whilst developing a vaccine, Strategy CCUS [2021] highlights how climate change and environmental solutions still lack a sense of urgency that is needed for drastically changing society, politics and industry.

Figure 5.4 provides an indication of the most influential factors Strategy CCUS has encountered in their experience with carbon capture, and with Strategy CCUS operating in many different regions, the interview and the experiences with CCUS is of a much more general nature. All six identified categories were discussed in the interview, and Strategy CCUS [2021] offer an explanation of why each of them can be perceived as a barrier, but in some instances also highlighting the fact that it might not be necessary for it to be a barrier. The social factor is considerably discussed, and the final conclusion is that inclusion of local stakeholders goes a long way in preventing issues such as public opposition and lack of trust, which is also why the enabling portion of the factor is slightly larger than the barrier. The environmental factor is discussed more in this interview in comparison, which is largely due to a discussion around economy being a barrier versus the environmental benefit arising from utilising the technology.

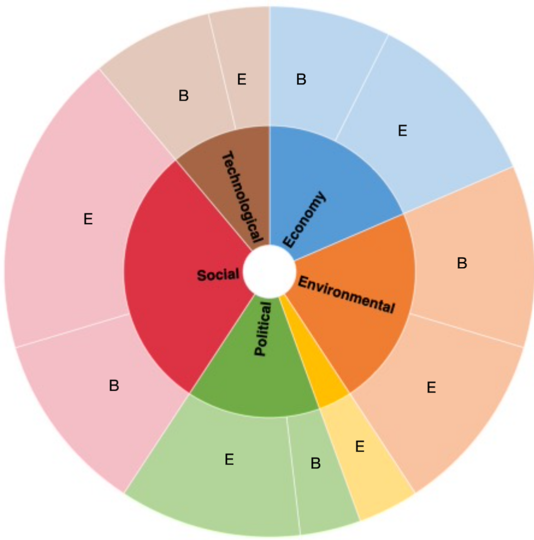

Figure 5.4. Pie chart illustration providing an indication of the barriers (B) and enablers (E) described during interview with Strategy CCUS.

5.4 Acorn CCS

The Acorn project commences in 2017 and is currently in the front end engineering design phase and awaiting the final investment decision. The organisation is divided into two entities (Acorn CCS and Acorn Hydrogen) covering 3 project phases. The first phase aims to build the necessary infrastructure to deliver CO_2 from a gas processing facility at Grangemouth to a distribution hub via pipeline at the St. Fergus Gas Terminal on the Scottish North Sea coast, with development of an offshore storage site planned. The second phase consists of developing a blue hydrogen facility to treat natural gas from the North Sea for the UK energy market, whilst the third phase initiates an investigation of direct air capture (DAC) [Acorn, 2021]. By 2030, the project aims to capture between 5–6 Mta of CO_2.

5.4.1 Motivations for the project

The UK has a mixed history with CCUS engagement, with a previous landmark government-run competition for CCS funding being cancelled days before the 2015 Paris summit [NAO, 2017], due to major uncertainties regarding the cost of technology back in 2015. Acorn [2021] stated that a key motivation behind the Acorn CCS project is to *"create an environment that was going to have [...] lower capital cost"*. By re-purposing existing pipelines, incorporating a significant amount of CO_2 and using existing knowledge of the offshore geology needed for storage, Acorn expects the overall project costs to fall whilst simultaneously helping to establish the necessary infrastructure for scaling-up in future [Acorn, 2021].

Another motivational factor for the Acorn project is that the UK is a country highly dependent on natural gas for domestic energy supply. Therefore, Acorn Hydrogen is interested in demonstrating the full-chain CCUS infrastructure needed for an industrial utilization strategy, focusing on how to use blue and green hydrogen within the national grid: *"in the UK we are largely all aligned with [...] blue [hydrogen] being an intermediary enabler of a much broader green economy"* [Acorn, 2021]. This highlights a highly contextual motivation being driven by existing and established technological systems.

5.4.2 The importance of context: political support and national policy

As documented by the cancellation of government funding in 2015, political support (e.g. section 4.1.5) for CCUS in the UK has been fluctuating significantly throughout the last 7 years. However, Acorn [2021] outlined how support has now positively shifted by stating *"I think there is a clear difference where we are politically now versus where we were 10-15 years ago.[...], there is a very different atmosphere now which is a result of the social movement on climate change"*. New UK legislation for net zero targets are also stated as a contributing factor for the increase in political interest around the technology, with the UK government also establishing clear policy around CCUS.

In particular, the UK government has initiated a cluster sequencing program in an effort to build a coordinating strategy. The aim of the sequencing program is to establish and organise CCUS around clusters (e.g. section 4.1.3), which are now seen as critical to the feasibility of CCUS in the UK [BEIS, 2018; Acorn, 2021], with each cluster able to take control and take the lead in developing knowledge and collaborations to aid their deployment. There appears to be a focus on creating a more uniform pathway and agenda around carbon reduction in the UK, with Acorn [2021] citing efforts around *"relationship development"* and developing a shared understanding of decarbonisation pathways to ensure *"the opportunity and the timings are lining up"* [Acorn, 2021]. Acorn [2021] elaborated that due to the cluster sequencing program, uniformity is secured on how CCUS leadership should be done, stating that *"the leader of the cluster aligns with the UK government to get the economic-financial contract in place"*. Acorn [2021] adds that it has not been easy to progress without a uniform strategy across the UK, but that the *"environment* *in the UK has been quite a collaborative space"* in comparison to the competitive environment seen previously.

5.4.3 Willingness and the business case

As political support and public awareness of climate change is increasing, so too is the interest and willingness from industry, with numerous industrial hubs initiating research and feasibility studies into CCUS [Global CCS Institute, 2020c]. Acorn [2021] expressed how industry wants to explore new possible business models due to the increasing pressure from climate activists: *"there is a strong general sense of unity among the industry that they need to come up with the solution"*, underscoring how industry is beginning to recognise the fact that *"climate change is a global problem so we need a global solution"*. Acorn [2021] see this interest as helping move the debate, and various CCUS initiatives, forward.

The Acorn project is planned to be scalable, with excess capacity in the re-purposed pipelines ensuring CO_2 from other countries can be accepted in future [Acorn, 2021]. Furthermore, the location of the planned CO_2 distribution hub — at the existing St. Fergus gas processing facility — ensures proximity to existing storage facilities in the form of depleted oil fields in the North Sea (e.g. section 4.1.3). Acorn [2021] elaborated *"Scotland as a country doesn't actually have that much CO_2 [...] which is why we are building a project which can receive CO_2 from all over the place"*. Both examples underscore how the Acorn project is seeking to minimise cost, essentially helping them overcome the previously identified *"capital cost issues"* [Acorn, 2021].

Of the five European CCUS initiatives assessed, only Acorn discusses in detail the planning and incorporation of CO_2 utilisation as part of their business case [Acorn, 2021]. Acorn Hydrogen aims to produce blue hydrogen by reforming natural gas, where CO_2 is essentially stripped out of fossil fuel gases as a waste product. [Acorn, 2021] explain that *"CO_2 will then be passed over the fence and be processed by the Acorn CCS infrastructure"*, whilst they continue to explore *"different options of what to do with the hydrogen [...] most likely, we can blend it into the national transmission system"*. The consideration of hydrogen for utilisation is of significance to the UK due to the continued use of gas both in industry and in domestic energy supply, with [Acorn, 2021] highlighting a growing interest around the technology in the UK due to its potential for broader decarbonisation. However, it was recognised that public perception issues regarding CCS exist from climate activists who say *"we are extending the fossil fuel industry"* [Acorn, 2021]. In this sense, Acorn is similar to Porthos, with a recognition of the uncertainty going forward in terms of technological solutions to climate change: *"CO_2 reduction from the atmosphere is probably going to be largely driven by technology solutions"*, but it is *"naive to think that anything is a permanent solution [...]. There is still so much innovation happening in carbon reduction and removal phase"* [Acorn, 2021].

Figure 5.5 provides an indication of the most influential factors that Acorn encountered in their experience with CCUS, and the factors that is discussed in the interview are predominantly perceived as enabling factors. Specifically, the technological factors are particularly positive in Acorn experience, something largely attributed to the fact that they are employing the utilisation aspect of CCUS, which increases the possibility of creating a business case. Additionally, the shift in political perception of CCUS in the UK has also provided Acorn with much needed support of the project.

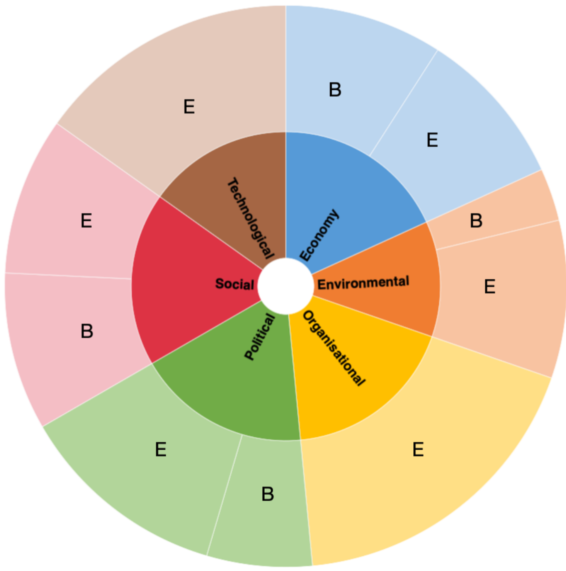

Figure 5.5. Pie chart illustration providing an indication of the barriers (B) and enablers (E) described during interview with Acorn.

5.5 Carbon Capture Cluster Copenhagen (C4)

The Carbon Capture Cluster Copenhagen (the C4) is a collaboration between various heat and energy production companies in the capital region of Denmark [Gullev, 2021]. The collaboration has an ambition to be able to capture 3 Mta of CO_2 by 2030, which amounts to 15% of the national emissions reductions target of 70% [Gullev, 2021]. The strategy of the C4 initiative is to form a carbon capture cluster due to the close proximity of the partners involved, in an effort to reduce infrastructure costs through economies of scale [Gullev, 2021].

5.5.1 Motivation for the project

The general motivation, as expressed both in a press release [Gullev, 2021] and during interview [C4, 2021], is to aid in the Danish ambition to reach 70% emissions reduction by 2030. By deploying CCS technologies in the companies involved in the collaboration, emissions are reduced in sectors that are otherwise hard to electrify such as waste-to-energy and district heating [Gullev, 2021]. Additionally, the motivation is also rooted in a desire to showcase the collaboration between public and private companies in CCS projects. The C4 initiative takes on a cluster approach to capturing CO_2, and some of their motivation is tied to promoting the development of CCUS, as well as developing, collecting and sharing knowledge on CCUS projects in the utility sector in Denmark [C4, 2021].

5.5.2 Anticipated barriers for CCUS in Denmark

The interview with the C4 collaboration highlights that the project is in its initial stage. Therefore, the discussion revolved largely around anticipated barriers, and initiatives that are necessary for the development of the infrastructure in Denmark — specifically in the capital region. The first issue discussed relats to regulatory uncertainties: *"[...] there is a lot of regulatory uncertainty, there is no regulatory framework"* [C4, 2021]. The regulatory framework is deemed a necessity for the further development of the project, because with the regulatory framework comes opportunities to finance the project through CO_2 taxes, raising funds or securing investments. The argument is that a regulatory framework would provide the future of carbon capture in Denmark with much needed stable conditions, and show potential investors that the technology has a role to play in emissions reductions in the coming years [C4, 2021].

While the regulatory uncertainties are highly contextually specific, the C4 collaboration highlights how the progress on CCUS in other countries has been beneficial to the development of the technology in a Danish context. Especially technical issues are seem to represent a lesser concern, because other projects in Europe have paved the way for the development in Denmark: *"Of course, there are some technical issues as well, but I think when looking at other projects, many of the technical issues has been solved — maybe not optimised — but at least there are solutions to it"* [C4, 2021]. The optimisation of the technology is described as relating to energy consumption, for which efficiencies were seen as a way of making CCUS more economically feasible, whilst also helping to tackle issues relating to public acceptance. For example, C4 [2021] saw public acceptance issues arising in relation to high energy-consuming technologies. Additionally, C4 also recognise that public perception issues related to specific industries (Aalborg Portland, Amager Ressourcecenter, etc.), could potentially be transferred into their interactions as organisations with carbon capture technologies, especially if large public funding was awarded. This point is exemplified in an exchange involving the decommissioning of an old oil rig in relation to CCS: *"People look at it like it is a way to avoid large spending in decommissioning this oil rig. So that is something that I think we will see in the public discussion"* [C4, 2021]. Seeing as they are in the beginning of doing a barrier-analysis, we were unable to discuss their approach to handling expected barriers.

Figure 5.6. Pie chart illustration providing an indication of the barriers (B) and enablers (E) described during interview with C4.

Figure 5.6 provides an indication of the factors that are anticipated to be most influential in the initiation and deployment of the project. It is not surprising that the most discussed factors are the ones that are most dominant in literature (see table 4.1), because as of yet, the C4 project has no experiences with deploying a CCS project. Therefore, most of the factors that are discussed in the interview are contextually specific to Denmark, but rather impressions gathered from literature or similar projects.

5.6 Revisiting the framework of influencing factors

Interviewing European practitioners provided an insight into the complex interplay between different factors impacting the overall feasibility of CCUS projects. Additionally, it highlighted the importance that national context has on whether a factor is experienced as a barrier or an enabling factor. Table 5.1 provides an overview of factors recognised by the European practitioners during interviews.

Table 5.1. Table of factors identified during interviews with European CCUS projects, based on the initial findings from chapter 4. 1 = Longship; 2 = Porthos; 3 = Strategy CCUS; 4 = Acorn CCUS; 5 = C4

Category	Factor	Project
Social	Trust	1, 2, 3
	Public perception	1, 2, 3, 4, 5
	Cultural elements	1, 3
	Knowledge	1, 2, 4, 5
Economic	Financial incentives	1, 2, 4
	Market incentives	1, 2, 3, 4
	Business model	1, 2, 3, 4
	Cost of technology	1, 2, 3, 4, 5
Technological	Technology readiness level	1, 2, 3, 4, 5
	Technology performance	4, 5
	Infrastructure proximity	2, 3, 4, 5
Environmental	Mitigation potential	1, 2, 3, 4
	Environmental risk	1, 2, 5
Political	Policy	1, 2, 4
	Regulation	1, 2, 4, 5
	Legislative framework	4, 5
	Political support	1, 2, 3, 4, 5
Organisational	Coordinating actors	1, 2, 3, 4
	Coordinating activities	1, 2, 3, 4
	Cluster	1, 2, 4

All interviewees touched upon more than one influencing factor identified in the literature review, and, as well as in literature, a pattern of more relevant factors emerged. All interviewees confirmed that a continued focus lies heavily on the economic dimensions of CCUS projects (table 5.1), expressing the importance of financial and market incentives for generating an interest in the technology. Furthermore, various alternative approaches to funding (e.g. subsidies versus government funds) were identified based on existing national financial instruments, highlighting the contextual nature of business models currently seen in countries like the UK and Norway. For example, in the UK, the business model is centered around the reuse of existing oil and gas infrastructure to minimise costs, with a large focus on the future potential of green hydrogen, which is to be a substitute for the continued use of natural gas for domestic heating [Acorn, 2021]. Conversely, significant state funding was shown to be crucial to a working business model where the state maintain ownership of the transportation pipeline [Porthos, 2021b].

Another factor identified as being key based on practitioner experience were CCUS clusters. Clusters was the least discussed factor in literature (figure 4.1), yet in the UK clusters form a key part of the industrial strategy for CCUS [Acorn, 2021; BEIS, 2021]. Clusters were also identified by Porthos [2021b] as an important enabler of CCS infrastructure in the Rotterdam context, with a shared-access pipeline provided by the state being key in gaining support from local industry (figure 5.3). Additionally, the results from interviews show the value that a dedicated coordinator brings to CCUS projects (e.g. coordinating actors; section 4.1.6). In particular, Gassnova saw their role as central to the ongoing coordination of the project, as well as to public-private negotiations [Gassnova, 2021]. This is perhaps unsurprising given the underlying reason for establishing Gassnova in the first place. However, the importance of coordinators was also discussed by Strategy CCUS who saw coordinators as necessary to *"ensure that everyone gets together around a table"* [Strategy CCUS, 2021]. Overall, the importance of coordinating actors expressed by several of the interviewees may also reflect a logical progression in knowledge regarding CCUS feasibility, with new factors being recognised as projects progress from a theoretical concept into a practical one. The importance given to several organisation factors by multiple interviewees therefore also emphasises the interrelated nature of the different factor categories, with clusters and facilitators helping to enable and establish working business models.

From the range of factors identified in interviews (table 5.1), political support and public perception appear to be the most interrelated ones, as well as the ones most influenced by national context. Negative public perception was shown to be a critical issue in determining the success or acceptance of CCUS, with a previous attempt in the Netherlands to develop CCS onshore ending with huge public opposition, which ultimately evolved into a lack of political support around CCS projects in the subsequent decade [Bellona, 2010; Porthos, 2021b]. Only after working intensively with various national NGOs promoting the benefits of CCS, was Porthos able to shift the debate in favour of the technology and thereby increase the political support (section 5.2.2). A similar relationship was identified by Strategy CCUS [2021] stating *"The political opinion is related to the year of election. They are just following [...] society"*, and Gassnova [2021] explaining that the country's broad political support and positive public perception is a results of a *"long tradition of CCS"*.

Figure 5.7 provides an indication of the most discussed categories throughout all interviews, highlighting the importance of the social, political and economic factors. The environmental and organisational factors were discussed to a lesser extend, but more so than in literature. Conversely, the technological factors were discussed less in interviews compared to literature, and the discussions revolve primarily around technological factors as enabling the deployment of CCUS. This suggests an evolution between the results from literature compared to the practitioners experiences, where the technological maturity of the technology is now less in doubt.

Furthermore, the interviewees also touched upon previously unidentified factors in the form of technology or carbon lock-ins and industrial willingness. Technology lock-in arises from a system of path-dependency where the adoption of a technology prevents, or inhibits, the development and deployment of preferable alternatives [Unruh, 2000]. In terms of sustainability, technology lock-ins can lead to more sustainable technological pathways being delayed or excluded from consideration. When a technology lock-in results in increased emissions, the effect is termed carbon lock-in [Seto et al., 2016]. Several of the interviews presented a discussion around

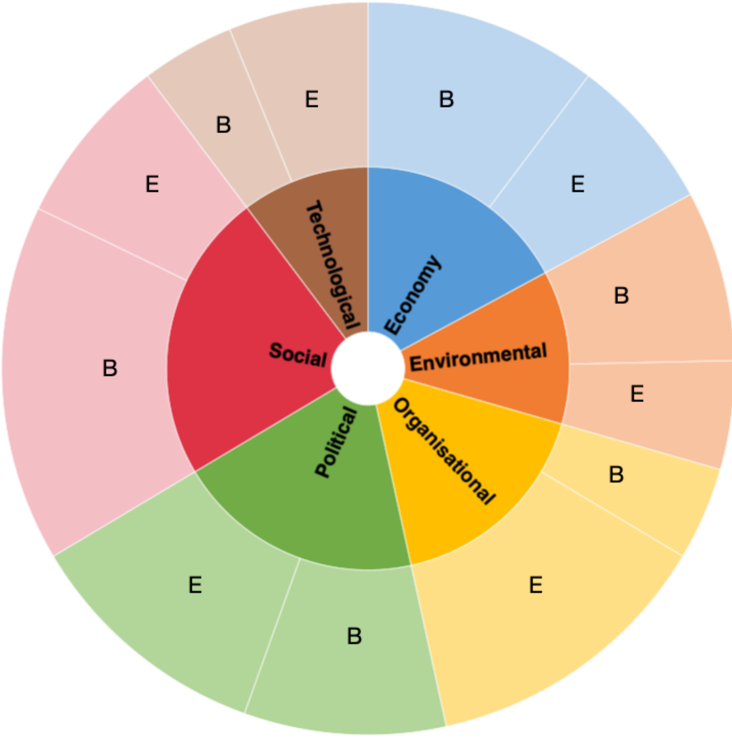

Figure 5.7. Pie chart illustration providing an indication of the barriers (B) and enablers (E) from all interviews.

technology or carbon lock-ins, with Porthos [2021b] describing how Dutch NGOs argues that the Porthos project will result in carbon a lock-in due to the projects focus around hydrocarbon refineries. Acorn [2021] describes how public perception issues arises from concerns over technology lock-in, highlighting how several UK activist groups see CCS as *"extending the fossil fuel industry"*. However, both projects describe CCS as an intermediate transition technology, needed until green hydrogen or renewable energy supply reaches a sufficient degree of maturity and capacity.

Industrial willingness was highlighted as being an enabling factor on the rise by Strategy CCUS [2021], stating that industry is putting pressure on the government in France to consider the technology as a solution for emissions reduction. And Acorn [2021] confirming that industries are beginning to recognise climate change as a global issue in need of a solution *"there is a strong sense of unity among the industry that they need to come up with the solution"*.

Table 5.2 represents an expanded framework including the newly identified influencing factors, technology and carbon lock-ins and industrial willingness.

Table 5.2. Expanded conceptual framework factors which impact the feasibility of deploying CCUS projects, divided into six categories: social; economic; technological; environmental; political; and organisational. Two additional factors identified through interviews are highlighted in red.

No.	Category	Factor
1	Social: *Societies awareness, perception and acceptance of CCUS as a climate mitigation technology*	**Trust**: between stakeholders and in technology **Public perception**: opinion of CCUS technology **Cultural elements**: tendencies for behaviour and social norms **Knowledge**: of the technology and processes
2	Economic *Factors impacting the economic viability of a CCUS project*	**Financial incentives**: monetary benefit to motivate engagement **Market incentives**: push-pull dynamics from market **Business model**: framework for delivering and capturing value **Cost of technology**: the economic costs of CCUS infrastructure
3	Technological *Technical issues affecting the uptake and dispersal of CCUS technologies*	**Technology readiness level**: maturity of technology **Technology performance**: how efficient a technology is **Infrastructure proximity**: distance of industry to key infrastructure
4	Environmental *How CCUS impacts the environment*	**Mitigation potential**: scale of GHG reduction possible **Environmental risk**: impacts from e.g. leakage **Technology lock-ins**: demanding continued use of a specific technology
5	Political *Legal instruments and the political setting of the host country*	**Policy**: a principle or stance guiding government **Regulation**: instrument for insuring compliance **Legislative framework**: system of legal documents defining rules **Political support**: degree that government supports something
6	Organisational *Factors facilitating CCUS engagement*	**Coordinating actors**: actors supporting a project or process **Coordinating activities**: actions supporting a process **Clusters**: geographic concentration of emissions or storage sites **Industrial willingness**: Industry motivation and engagement

Issues and uncertainties in a Danish context 6

This chapter is dedicated to answering the third research question by assessing the issues and uncertainties of developing CCUS in a Danish context. The assessment is based on factors from literature, which have been confirmed and expanded by interviews, as well as contextual data highlighting the current landscape in Denmark.

6.1 Social issues and uncertainties

Both literature and European practitioners attributed significant value to the social factors impacting CCUS. In Denmark, there are systems and laws in place to protect the rights and interests of the public (e.g. forvaltningsloven), which helps to create *trust* between the public and government. This focus on trust between the public and government was identified as important for *public perception* (section 4.1.1), with transparency and citizen involvement being key in securing positive public perception. This was something Strategy CCUS [2021] suggested should be strongly considered when planning CCUS projects: *"we should construct projects with society [...] by involving them in the beginning of the project"*. Furthermore, C4 also saw potential public perception issues arising in Denmark as a results of a lack of trust in specific industries [C4, 2021].

Previous experiences with carbon capture in Denmark shows that negative public perception from local communities plays an important role, with public opposition causing the only previous investigation into CCS at Vedsted to be rejected [Stigson et al., 2012]. Furthermore, other previous large-scale infrastructure projects in Denmark have faced similar issues, most notably the investigations into shale gas in Jutland in 2011–2012. Here, the Minister of energy at the time, Martin Lidegaard, had to cease awarding any new licences after realising that no public debate had occurred around shale gas, with future activities ultimately stalling due to widespread public opposition [Becker and Werner, 2014]. Despite this history, the public perception toward CCUS in Denmark remains unclear, with a lack of public debate and a lack of understanding around the current level of public *knowledge* of CCUS [DCCC, 2021a]. In Denmark, public perception issues were largely described as relating to the question of onshore vs. offshore storage. For example, Nordic/CPH [2021] stated: *"Forget it! [onshore storage] The plans in North Jutland in its time raised public opposition, with good reason, which showed that it is not politically viable"*. This view was also put forward by DCCC [2021a] stating *"So maybe it is more expensive to do offshore storage but maybe it is the best place to start due to public opinion"*. Public perception as being a possible make or break point for projects has also been debated in other contexts. For example, Energy CLUSTER Denmark [2021] stated that *"technical solutions are being explored because behavioral changes are simply too difficult"*. This describes how initiatives relating to behavioural change, which may hold greater value than technological solutions, are often excluded from consideration due to the fact that the public are not adaptable to change. [Energy CLUSTER Denmark, 2021].

Cultural elements is a difficult factor to assess in a Danish context, as literature is yet to tackle how culture affects CCUS in Denmark. However, similar large scale energy and infrastructure projects (e.g. nuclear power) have been rejected due to uncertainties regarding the risks associated with the technology [Søholm, 2012]. History repeated itself when CCS was first investigated in Denmark (e.g. the Vedsted-case, section 1.2), because of concerns associated with possible CO_2 leakages and the damages it could bring. Conversely, implementing CCUS can be seen as an option to continue business-as-usual, and the increase in household waste — despite numerous campaigns to reduce national waste [Eurostat, 2021] — points to the fact the Danish culture may be reluctant to behavioral changes.

6.2 Economic issues and uncertainties

Presently, various *financial incentives* are appearing in Denmark, including a 210 million DKK fund to support the development of offshore storage sites, several individual governments grants (e.g. for GreenCem via the EUDP) and up to 820 million DKK per year from 2024 to finance CCUS infrastructure projects [KEFM, 2020]. As shown by international projects like Porthos [2021b], such funding is critical in minimising the overall *cost of technology* to gain the interest of industry, thus Denmark has already made steps toward minimising the issues relating to financial support.

However, a more pressing issue impacting CCUS feasibility in Denmark are outstanding questions regarding *market incentives*. Recently, criticism emerged over the governments green tax reform, which failed to set concrete measures for introducing a CO_2 tax despite committing to one in the long-term [Skatteministeriet, 2020]. DCCC [2021b] state that a *"gradually increasing, uniform and significant tax on all Danish greenhouse gas emissions"* would represent the right *market incentive* to encourage fair dearbonisation across multiple sectors whilst accelerating the deployment of CCUS. DCCC [2021b] argue that this should be introduced within the near-term to allow organisations time to prepare and adjust to such a tax. However, several parties have been critical of a CO_2 tax, with the Conservative Peoples Party (Konservativ Folkeparti) highlighting the risk of either carbon or investment 'leakages' e.g. the relocation of polluting industries to jurisdictions with less oversight and a reduction in investments [Gianoli and Bravo, 2020; Weiss, 2021]. A mechanism for minimising the risk of leakage has been proposed by the EU in the form of a carbon border adjustment mechanism [EU, 2020], however uncertainty persists as to what the long-term impacts would be by introducing a CO_2 tax in Denmark. Ultimately, balancing financial incentives (e.g. carrot) with sufficient market incentives (e.g. stick) could prove critical for Denmark in avoiding what Porthos [2021b] described as outrage from the public following the application for €2.1 billion in state subsidies by four hydrocarbon refineries.

The ETS price is also expected to further encourage interest in CCUS in Denmark, with Remmem [2021] stating how the current near record price of €51/t CO_2 would *"of course influence what the companies are interested in doing"*. A high ETS price is therefore seen as an essential market incentive for improving the overall business case for CCUS. However DCCC [2021a] suggested that even the current ETS price *"would only cover the fossil emissions"*, leaving costs unaccounted for. This was an issue also described by several international (chapter 5) and national CCUS practitioners [AffaldVarme Aarhus, 2021], with the business case for utilisation currently seen as the most problematic in Denmark due to issues relating to scaling up the technology to bring down the price [DCCC, 2021a]. One way of improving the business case for CCUS may be through establishing new market incentives, such as greater sustainable public procurement and an increased demand for new sustainable products. Denmark recently published a new agreement covering all building works and public infrastructure projects, which includes strict criteria on the amount of CO_2 emissions associated with each square meter [Indenrigs og Boligministeriet, 2021]. The agreement has been met with enthusiasm from industry, including Denmark's only cement manufacturer, Aalborg Portland, who see it as critical for *"contributing to a rising demand for sustainable solutions"* across Danish society [Dansk Industri, 2021]. Such agreements set an important precedent and could therefore be applied to other industries in order to drive demand for new products, such as synthetic fuels derived from CCU processes. Furthermore, other European countries are exploring similar initiatives [BEIS, 2020], thus there is a potential to establish a European-wide market for low carbon products from CCUS value-chains. Ultimately, until a more detailed vision of how Denmark intends to pursue CCUS is set, addressing the technicalities and concerns of any potential *business model* remains challenging despite the importance given to the issue by numerous interviewees [e.g. Gassnova, 2021; Porthos, 2021b; Acorn, 2021; AffaldVarme Aarhus, 2021].

6.3 Technological issues and uncertainties

The results from the literature review shows that technological factors, particularly *technology readiness level*, as a barrier to deploying CCUS, because the technologies needed to capture CO_2 are immature and uncertain. However, European CCUS practitioners highlight how the technologies are largely mature [e.g. Acorn, 2021; Porthos, 2021a; Gassnova, 2020], and seen more as an enabler at the current stage of CCUS projects in Europe (figure 5.7). Yet, Acorn [2021] highlights how new emerging technologies (e.g DAC) remains less mature than post-combustion carbon capture systems. Presently, DAC technology is seen as providing only a small proportion of the total CO_2 emissions reduction needed globally to reach the climate targets of the Paris Agreement [IEA, 2020c]. However, DCCC [2021b] recognise the potential of DAC, describing the technology as useful for offsetting emissions from the Danish agricultural sector toward 2050.

While European practitioners described the technological maturity as sufficient for deployment, attention was drawn to issues relating to *technology performance*, with C4 [2021] stating that some important *"technical issues have been solved [but] maybe not optimised"*. A key example hereof, is the large amount of heat that MEA post-combustion capture, the most mature technological process, currently requires. MEA post-combustion carbon capture is known as an energy-intensive process, with 'amine scrubbing' (i.e. the chemical reaction between solvent and flue gas) alone being responsible for between 50—80% of the total energy consumption of the process [Plaza et al., 2020]. This large energy consumption particularly remains an issue in cement factories, where excess heat is often reused in the pre-treatment process of the cement. Furthermore, in Denmark, the only cement manufacturer, Aalborg Portland, currently contributes approximately 28% of all heat going into the district heating system in Aalborg [Aalborg Portland, 2020], meaning that the diversion of excess heat to carbon capture processes would potentially impact local heat supply. Technology performance issues are also recognised by Gassnova, with carbon capture from the Norcem cement factory only able to capture 40% of the total emissions due to similar energy concerns [Bjerge and Brevik, 2020]. These examples underline important areas for future optimisation which need consideration when planning CCS at scale, and measures to optimise the technology in relation to technology performance and energy consumption are being investigated. A recent Horizon 2020 project called ConsenCUS comprises a consortium led by Danish researchers together with stakeholders across the globe. The aim of the project is to demonstrate new electricity-based technologies for carbon capture, utilisation, and storage, in order to provide a more sustainable and even climate neutral method for CO_2 reduction [DTU, 2021]. In Denmark, a demonstration plant is planned at Aalborg Portland, with renewable energy sources for powering the CO_2 capture process planned.

The objective of ConsenCUS is to create mobile carbon capture plants, which would aid in decreasing concerns around *infrastructure proximity*. Infrastructure proximity is well recognised by the European practitioners as a potential barrier, because the location of a capture plant relative to the infrastructure needed to transport and ultimately store or utilise the CO_2, can create the basis for a lower cost. This is supported by the stakeholders from a danish context with DCCC stating *"If you are close to the sea then you have other transportation possibilities or if you have like a pipeline laid out somewhere, maybe if you are close to that you have an advantage"* [DCCC, 2021a], highlighting that having multiple options in terms of transport will create the basis for a more agile project.

6.4 Environmental issues and uncertainties

Gassnova [2021] highlighted the importance of investigating life-cycle emissions to assess the *mitigation potential* of CCUS value-chains, drawing attention to emissions associated with CO_2 transportation by ship and the life-cycle impacts of amines — the absorbent used to remove CO_2 from industrial flue gases from MEA carbon capture. Presently, there are no CCUS initiatives in Denmark advanced enough to be performing life-cycle analyses, however the mitigation potential of CCUS is a subject of interest in Denmark. This is due to a growing focus around negative emissions technologies such as bioenergy with carbon capture and storage (BECCS), a technology the IPCC [2018] see as essential in reaching net zero targets. The DCCC also point to negative emissions technologies as necessary for offsetting residual emissions in order for Danish society to reach net zero by 2050 DCCC [2021a].

Despite this consensus, BECCS has been criticised in recent years due to the *environmental risk* posed by the technology in terms of the potential for increased demand for biomass feedstock to result in significant global land-use change [Field and Mach, 2017; Harper et al., 2018]. Another important, albeit somewhat contested, environmental risk relates to concerns from CO_2 leakage. The risks from CO_2 leakage, described by Gassnova, Porthos and the DCCC, was at least partly responsible for the observed public opposition at Vedsted in 2011 regarding onshore storage [Stigson et al., 2012]. Although seen as a small risk [Harding et al., 2018], it therefore remains important that the Danish authorities and research institutions such as GEUS demonstrate the safety and integrity of underground storage of CO_2 to positively contribute to the debate around CCS in Denmark.

The European practitioners experiences also highlighted a debate around *technology lock-ins* from CCUS (section 5.6). In Denmark, CCUS is being considered across different sectors with inherently different sources of emissions. For example, C4 represents a large collection of predominantly waste-to-energy plants in Copenhagen (e.g. Amager Ressourcecenter), whilst the the GreenCem project is investigating carbon capture from cement manufacturing. Furthermore, AffaldVarme Aarhus — a waste-to-energy and biomass plant — have also expressed interest in the technology. Technology lock-ins from CCUS remains a poorly studied subject and were not described by any of the European interviewees as an issue in terms of feasibility. However, technology lock-ins from CCUS are seen as a risk by several Danish actors [DCCC, 2021a; Remmem, 2021].

One sector for which technology lock-ins may have implications regarding the feasibility of CCUS from a society perspective is the waste-to-energy sector. In 2018, Denmark imported 975.000 tonnes of waste for use in the waste-to-energy market [Miljøstyrelsen, 2020], which today accounts for 20% of all district heating supply and 5% of electricity [Dakofa, 2021]. Remmem [2021] discussed how as a society, we should focus more on *"waste prevention and minimization"*, rather than building a system *"that will lock us into [...] waste energy"* for years to come. Indeed, whilst average waste generated in the EU per capita has remained stable over the last 15 years, in Denmark the level of waste generated per capita has actually increased by 15% over the same time-frame and is the highest of any EU country [Eurostat, 2021]. A recent political agreement has taken aim at the Danish waste-to-energy sector, with the Danish climate minister, Dan Jørgensen, introducing new efforts to improve circular economic waste opportunities, stating that we need to *"stop importing plastic waste to dispose of it at the expense of the climate"* [State of Green, 2020]. However, AffaldVarme Aarhus [2021] made the case for CCUS and waste-to-energy in Denmark, highlighting that a cleaner waste incineration process would benefit society, *"because of the energy system as it is and also because of societal behavior ... there will still be waste after 2030"*. Overall these contrasting arguments highlight continued uncertainty over a) the future direction of the waste-to-energy sector in Denmark, b) the potential impacts of locking Denmark into waste importation and incineration for decades to come, and c) the potential for additional lock-ins arising from other sectors. This was underscored by DCCC [2021a] who described how Denmark currently imports the majority of its biomass feedstock, highlighting that if global demand for biomass were to increase, prices would be pushed up. Coupling carbon capture to emissions from biomass in Denmark could therefore result in an expensive technology lock-in, where biomass is priced out of Danish energy systems compared to alternative renewable technologies.

6.5 Political issues and uncertainties

Political factors were widely discussed in literature (figure 4.1) and were shown to have been key to the feasibility of current CCUS initiatives in Europe (table 5.1 and figure 5.7). Denmark was recently ranked as the eighth most progressive nation in terms of its CCUS *policy* environment [Global CCS Institute, 2018a], based on its ambitious 2030 climate targets and previous work investigating CCS storage sites as part of the 2016 NORDICCs project.

In Denmark, both the Paris Agreement and Denmark's 2030 climate strategy were seen as key drivers for CCUS engagement [AffaldVarme Aarhus, 2021]. However, the DCCC have criticised the Danish governments lack of concrete strategy for CCUS, as well as the over-reliance on what remains a largely unproven technology [DCCC, 2021b]. When assessing the political factors impacting CCUS feasibility in Denmark, several areas of uncertainty therefore emerge. Firstly, the uncertainty identified in section 6.4 regarding waste importation and incineration highlights a need for clear policy to determine the future application of carbon capture technologies in Denmark [e.g. State of Green, 2020]. This is further complicated by conflicting statements of *political support*, with Dan Jørgensen underlining the need to reduce waste importation whilst at the same time championing the C4 [EnergyWatch, 2021], a cluster comprising multiple waste incineration plants including the controversial Amager Ressourcecenter [Madsen, 2019]. A second area of uncertainty identified relates to CO_2 storage, with DCCC [2021b] describing long term storage as unavoidable in order to reach Denmark's 2030 climate target. Yet, there remains continued uncertainty regarding the policy and *regulation* governing CO_2 storage sites in Denmark, including removing the legal barriers to storage and clarifying issues regarding ownership [DCCC, 2021b]. This is despite the fact that the Danish government has established a 200 million DKK fund to support the development of storage sites in the North Sea between 2021–22 [Danish Ministry of Finance, 2020]. However, whilst policy uncertainty around CO_2 storage persists, the establishing of such a significant fund does signal clear political support around a specific technology. National political support was identified by all five CCUS initiatives interviewed (table 5.1) and has been shown to be a project stopper in both the Netherlands and in Denmark previously [e.g. Stigson et al., 2012].

In Denmark, the establishing of a North Sea fund [e.g. Danish Ministry of Finance, 2020] combined with the inclusion of CCUS in the national climate road-map [e.g. KEFM, 2020] does indicate widening political support for CCUS. However, it can be argued that political support for CCUS has been slow to materialise, resulting in an ever-growing number of largely bottom-up research initiatives (e.g. GreenCem, ConcenCUS, Greensands, C4, AffaldVarme Aarhus, GreenLab Skive). Whilst bottom-up initiatives are important for increasing the motivation of different market actors and giving them a voice, the proliferation and number seen in Denmark risks slowing the strategic development process due to competing interests and visions for CCUS [Arts and Tatenhove, 2004]. For example, a recent report from Danish Energy (Dansk Energi) [Dansk Energi, 2021] shows significant interest in the technology due to its potential to produce electrofuels through Ptx utilisation methods, which can be argued represents a different focus to a more climate-based emissions reduction strategy. This emphasises a wider ongoing national debate around the potential of CCUS under different scenarios (see section 6.4).

6.6 Organisational issues and uncertainties

The organisational aspects of deploying CCUS was one of the least discussed aspects in literature (figure 4.1), yet the interviews with European practitioners highlighted their value, with Gassnova [2021], Porthos [2021b] and Strategy CCUS [2021] all emphasising the need for *coordinating actors* and *coordinating activities* in avoiding other issues emerging. A clear example of their value was described by both Strategy CCUS [2021] and Gassnova [2021], who pointed to the fact that a strong coordinating actor had been essential in bringing stakeholders together whilst creating a foundation of trust between government and industries that removed uncertainties in relation to the different phases of CCUS. In Denmark, there is still no clear or central coordinating actor, resulting in the emergence of largely industry-led *clusters* across the country.

Numerous European practitioners highlighted clusters as being an essential part of deploying CCUS (table 5.1), because larger concentrations of of emissions, shorter transport distances to utilisation facilities or effective storage sites, and shared infrastructure improves the efficiency and decreases the cost of CCUS projects. In Denmark, several clusters have already emerged, with the C4 initiative in Copenhagen and GreenCem in Aalborg. Additionally, the Horizon 2020 project ConcenCUS is investigating the possibility of synergies in Aalborg through a possible utilisation and storage value-chain. The aim of the project is to capture CO_2 from large inevitable emitters, using renewable energy to power the capture facilities. In an interview Aalborg Portland's CEO states: *"The project will also explore possible synergies in cluster and* *value chain collaborations, which we consider essential if we're to succeed with CCUS on a large scale in North Jutland, because it will require the involvement of several players"* [DTU, 2021]. In this scenario, a coordinating actor is needed to identify, include and ultimately oversee the numerous actors involved in this consortium and while emissions clusters are starting to form in Denmark, questions remain around the potential transport technologies, utilisation hubs and storage facilities.

In Denmark, *industrial willingness* in relation to CCUS projects is seemingly increasing, with numerous industries throughout the country looking to investigate the possibility implementing carbon capture. The C4 project in Copenhagen has been presented to the public, and investigations related to its feasibility as well as a barrier analysis has been initiated. In Aalborg, a consortium of different partners are set to investigate the feasibility of carbon capture in the region, involving both Aalborg Portland and Reno Nord (waste incineration). Additionally, during a meeting with AffaldVarme Aarhus, they expressed interest in the technology and its potential as well, stating a desire to involve other larger emissions sources in the area. However, according to C4 [2021] the industrial willingness in Denmark is conditioned on the economic conditions that arises from future legislation on the subject.

The current state of the development in Denmark is leaning towards a bottom-up approach, because the initiatives are coming from industry rather than government. A bottom-up and market driven approach to industrial symbioses are highlighted by researchers as being stronger than a top-down approach, because a top-down approach runs the risk of not adapting to changes in the market [Fischer and Krausing, 2018]. However, as also emphasized in interviews, a top-down approach can provide clarity in terms of a clear goal and strategy, as well as provide an impartial approach to setting up timetables, tasks, etc. Additionally, if all involved parties are trying to get heard and some are operating out of personal interest rather than a common goal, then it can lead to division and conflict among the stakeholders [Malsam, 2019]. The need for an organisational actor or facilitator in a Danish context when involving multiple industries has also been expressed in *Bæredygtige Synergier*, an industrial symbiosis project in Aalborg, where having a facilitator is highlighted as bringing efficiency and a clear focus on intent to the project [COWI, 2020].

The current bottom-up approach in Denmark is beneficial in the sense that it drives the technology forward, and many actors are developing an interest in the subject. However, for CCUS to succeed in Denmark, some version of a facilitator or coordinating actor is necessary, to avoid complications around infrastructure, common goals and the chicken-and-egg-paradox.

6.7 Key issues and uncertainties in Denmark

The analysis underscores a growing interest and activity around CCUS in Denmark in response to national climate targets and highlights progress within key areas, comprising financial incentives, industrial willingness and political support. However, whilst progress is being made in some key areas, many uncertainties and other issues remain.

A key area of continued uncertainty related to the social factors, which in Denmark remain largely unexplored. This is despite the fact that both international and national experiences have shown negative public perception resulting in a lack of political support, which when combined can be a project stopper. Presently, political support appears to be increasing, yet a clear national strategy or policy around CCUS has not been defined, leading to uncertainties around the future of the technology. In particular, the analysis identified several potential technological lock-ins relating to the application of CCUS to key national sectors, including waste-to-energy and biomass. Research has shown potentially severe and currently unforeseen environmental impacts occurring in the future from such lock-ins, emphasising the need to investigate CCUS from a broader societal perspective.

Discussion of results 7

Developing a conceptual framework of CCUS barriers and enablers based on a literature review (chapter 4) and interviews with European practitioners (chapter 5) highlights the value in applying international experiences to an assessment of CCUS feasibility in Denmark.

7.1 International perspectives on CCUS

The international experiences demonstrate that political, social and economic factors represent a critical support base to the deployment of CCUS. A lack of consideration of factors within these categories can therefore result in projects stalling or being cancelled. Furthermore, factors grouped under the environmental and organisational categories are seen as helping optimise the feasibility of CCUS projects. Whilst not necessarily critical, factors such as mitigation potential, technology lock-ins and coordinating actors can help promote sustainability whilst working between different sectors of society to facilitate a project. Technological factors were given different significance by different stakeholders: in literature, the technology readiness level was viewed as a barrier to CCUS, whilst experiences from European practitioners points to a mature technology acting as an enabler pulling developments forward. This conflicting result raises several important questions. For example, does it show that the technological maturity, and therefore technology performance, is now sufficient enough to not be a feasibility issue? Or are the European practitioners currently working with the technology simply 'technology promoters'? Here, it is worth highlighting that all five European initiatives interviewed are working with the post-combustion MEA technology, which has a technology readiness level of 9 out of 9 [Bui et al., 2018]. However, other potentially more efficient carbon capture technologies with lower technology readiness levels exist, yet only Acorn [2021] and C4 [2021] highlighted performance issues suggesting that this category is influenced by the technology choices of the practitioners in question. Despite this, the current maturity and availability of MEA shows technological factors to not be an issue to CCUS feasibility in general, with additional factors such as infrastructure proximity primarily relevant to the design and implementation of CCUS value-chains.

By synthesising the results from chapter 4 and chapter 5, the relative hierarchy of factors impacting CCUS feasibility can be visualised (figure 7.1). The European experiences now show that it is only the political, social and economic categories which are critical to the emergence of CCUS. However the application of the framework to the Danish landscape also shows that the environmental, organisational and technological factors play an important role in determining the overall feasibility of a CCUS project for society. The findings from Denmark therefore echo the results from Gough et al. [2017] and Pihkola et al. [2017], who see the need to judge CCUS feasibility on criteria broader than simple techno-economic assessments. These findings are discussed in greater detail below.

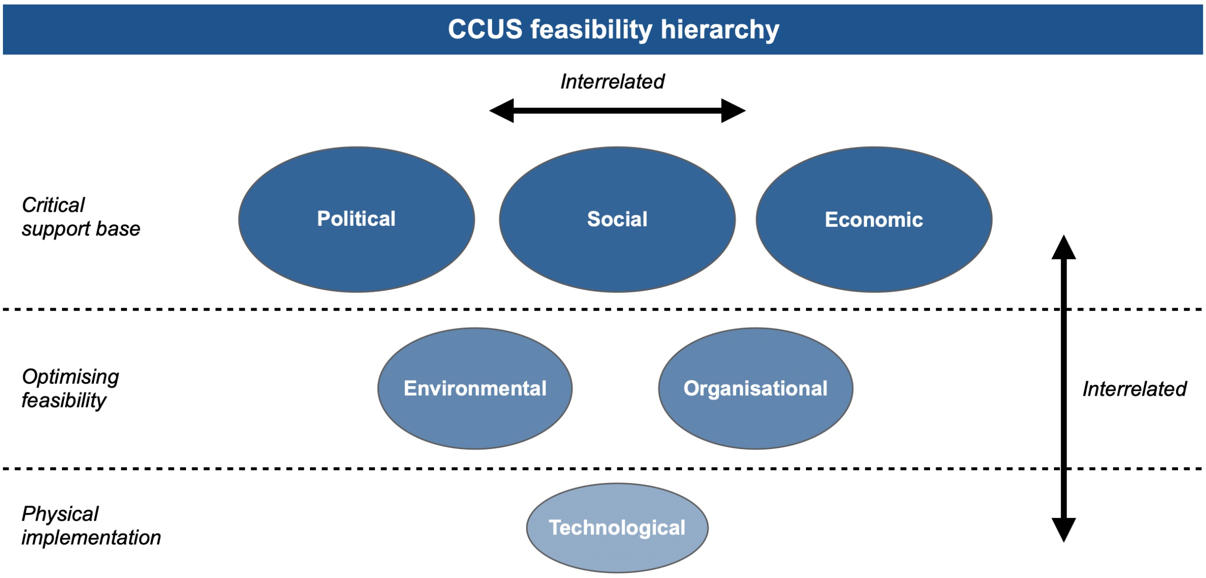

Figure 7.1. A conceptual framework of factors impacting CCUS feasibility and their relative hierarchy in a Danish context, based on international experiences.

7.2 CCUS in Denmark: the way forward

Applying the framework analysis to Denmark helps to identify key feasibility issues facing CCUS projects in the coming years.

Various social factors (e.g. trust, knowledge and public perception) remain unexplored in Denmark despite the fact that negative public perception has previously impacted CCUS development in Denmark. Aside from fear of CO_2 leakage and general opposition to onshore storage, the consensus of the public was also that CCS was an unsustainable solution in the green transition [Ditzel, 2020]. However, the findings from international practitioners show that public perception can evolve depending on contextual factors such as trust, culture and political support (e.g. Porthos [2021b]). This finding confirms earlier studies which show the importance of national context when assessing public perception [e.g. Karimi and Toikka, 2018] and raises an important question of whether the Danish public perception of CCUS could have changed, and if so why? Based on the analysis, it can be be argued that the critical support base of social factors remains unclear in Denmark, thereby posing a risk to the overall feasibility of domestic CCUS projects and a key area of future research.

Uncertainty within the economic support base (figure 7.1) was also identified in Denmark in relation to CO_2 taxes as a market incentive. Interestingly, the results from the European practitioner interviews do not show a consensus around market incentives — in both Norway and the Netherlands, ambitious CO_2 taxes are under consideration, whilst in the UK, CO_2 taxes were not discussed. This indicates that a CO_2 tax in Denmark may not be essential for CCUS feasibility. However, anticipation of a future CO_2 tax [e.g. DCCC, 2021a] cannot be ruled out as helping to drive current levels of interest in Denmark. Conversely, financial incentives which support CCUS research and development are now rapidly appearing. This is interpreted as being helped by widespread political engagement, and shows how both the political and economic support bases for CCUS are both interrelated and rapidly solidifying (figure 7.1). Ultimately, based on the international findings, generous financial incentives as well as clear business models are likely to prove critical to evolving CCUS from a national debate into a clear climate action plan. Despite this, a clear national strategy and accompanying policy is still absent, something which several Danish stakeholders described as a key requirement and an outstanding risk for CCUS feasibility [AffaldVarme Aarhus, 2021; C4, 2021]. Based on the historical context of large scale infrastructure projects (e.g. nuclear, shale gas and CCS) in Denmark, combined with international experiences, future policy discussions should therefore examine the public perception issues around onshore vs. offshore storage as well as addressing issues relating to funding and the business model.

Environmental and technological factors were not deemed critical based on practitioner experiences. However, an examination of these categories in a Danish context uncovered a debate around technology lock-ins and technology performance, which remains largely absent from the political arena. Contrasting opinions on the role of CCUS for reaching emissions targets in Denmark therefore exist. For example, Remmem [2021] described CCUS *"as a technology fix, and as something that is perhaps even a bad excuse for not doing all the possible things you can do right away"*. This opinion is best considered in relation to the ongoing debate around waste importation and incineration. If Denmark has to import waste to help power key waste incineration plants (e.g. Amager Ressourcecenter) despite being Europe's largest producer of household waste, does it still make sense to build expensive carbon capture units at these same sites? Or should society instead focus on reducing emissions through waste reducing initiatives? This debate also highlights the potential for numerous lock-ins to emerge. For example, the combination of CCUS with waste-to-energy plants could lock in existing behaviours around waste and thereby prevent new patterns of behaviour emerging. Studies have confirmed this effect by showing how Dutch policy favouring waste-to-energy may be preventing the emergence of local circular economy programs [Van de Berghe et al., 2020].

The conflicted opinions on the role of CCUS in Denmark is exemplified by DCCC [2021a], who suggested that the 'low hanging fruit' of emissions reductions have already been utilised, meaning that other measures are now necessary. However, as described alternative routes to a 70% reduction do still exist. Yet, behavioural changes are seen as a more challenging route to societal development, with 'technology fixes' offering what Lyons [2011] describes as a *"convenient perpetuation of business as usual"*. The growing European interest around CCUS may therefore be a reflection of the realisation that the time-frame for reducing emissions is closing and that CCUS now represents the easiest path forward. The discussion of what to do to reach the 70% emissions target in Denmark therefore appears to still be centered around the "hockey-stick" principle, where CCUS is seen as an 11th hour saviour [e.g. Nissen, 2020; Sæhl, 2020].

Remmem [2021] elaborates on the dangers of the hockey stick principle and the general lack of progress around CCUS over the last 14 years, stating that: *"not much has happened in the meantime [since Vedsted was cancelled]. I don't think that we should rely too much on the technology"*. However, what would happen if Denmark were to delay or stop investigations into CCUS? C4 [2021] view this as a considerable threat to meeting national climate targets, stating that *"one of the dangers there is, is that we wait too long until we decide which solution we want to rely on"*. This raises another important question regarding technology choices, due to the fact that potentially superior technologies may emerge in the coming decade. Should we wait for the "right" technology to appear or is it best to simply deploy existing technologies to help establish the necessary CCUS infrastructure and legislative frameworks? Various European practitioners did highlight the long development times of CCUS projects, meaning that if society fails to act now we risk postponing such projects further making it yet harder to abate emissions by 2030 and beyond.

It is hard to define what is needed technologically for reaching the Danish 2030 climate targets, with European practitioners concurring that CCUS cannot make it on its own. However, what is clear is that the current narrow focus by numerous international CCUS projects on political, economic and social factors risks excluding important aspects, such as technology lock-ins and technology performance, from the decision-making process. Hence, an argument can be made for the consideration of all CCUS feasibility categories in an iterative manner, where new insight can help inform and adjust policy, where needed. This could then help ensure that the Danish society evaluates CCUS within the broader context. [Whitmarsh et al., 2019].

7.3 Methodological and theoretical reflections

This section includes discussions on the use of methods throughout the study, as well as reflections regarding the overall scope of the research.

In terms of capture technologies, the scope of this study was largely focused on post-combustion MEA carbon capture due to the maturity of the technology [Bui et al., 2018], and the fact that all full-scale European CCUS projects interviewed were working with the technology. However, small scale demonstration projects using alternatives such as oxy-fuel carbon capture exist globally (e.g. Callide Oxyfuel Project). Whilst the literature review incorporated data from different types of capture technologies, the interviews could have been expanded to include new perspectives from practitioners working with alternatives. This may have broadened the results and given new insight into certain feasibility factors (e.g. technology performance). Future studies could therefore expand upon this work by assessing the feasibility of alternative capture technologies using the framework developed in this study. This is also important because there is a risk that society becomes locked in to using MEA capture technologies if other, potentially superior, alternatives are gradually excluded from debate [i.e Seto et al., 2021]. Additionally, the study may have benefited from including Europe's oldest operational CCS project, Snøhvit. Here, insight into operational issues and detail regarding storage challenges would have provided a longer term perspective not currently afforded by the more recent phase of development. Furthermore, the number of interviewees could have been expanded to include stakeholders from governmental agencies in Denmark, as well as a more in depth interview with an NGO. This may have provided additional reflections on barriers and enablers to CCUS in Denmark and further clarified the CCUS feasibility hierarchy (figure 7.1). Additionally, the inclusion of C4 in assessing the importance of national context in chapter 5 may have been premature, as the project is at its initial phase and has yet to experience barriers and enablers.

The term 'feasibility' was purposefully excluded from the search string used during the literature review. This decision was based on the premise that feasibility usually focuses on techno-economic considerations [e.g. Pihkola et al., 2017], which could have biased the search string results with an emphasis on technical and economic papers. Instead, the study focused on search terms which by their nature imply feasibility (e.g. enabler/barrier). However, by excluding the term feasibility from a study interested in feasibility, relevant papers may have been excluded from consideration. Here, an additional search string including the term could have been used to compare the results with the search string used in order to assess how the search term may have altered the results.

While the literature review and interviews within a grounded theory approach has its focus on allowing the data to tell its own story, the interpretation, coding and categorisation is ultimately carried out by researchers. The grounded theory approach therefore opens itself up to issues relating to bias and subjectivity. Efforts where made to increase objectivity, with encoded passages only coded as barriers and enablers when discussed in relation to negative or positive experiences. All neutral discussions of factors (e.g. how a project is structured without reference to merits or drawbacks) were excluded in the coding. However, an argument can be made that describing specific aspects of a project without referring to negative experiences can be interpreted as the interviewee referring to an enabling factor. These sections were therefore coded and included in the analysis. Throughout the interpretation and coding, efforts were also made to ensure consensus from all researchers in the identification and categorisation of the factors, as it became clear that different academic backgrounds resulted in differences in the perception of different factors. Therefore, it should be noted that if the methods were carried out by other researchers, the results may vary slightly. However, the overall results and identified factors would in all probability remain the same.

Besides semi-structured interviews with both international practitioners and Danish stakeholders, a meeting regarding potential collaboration with AffaldVarme Aarhus was held. At the meeting a presentation of preliminary findings were given, and — aside from the presentation — everything has been transcribed. However, as it did not follow an interview guide the transcription has been included in the appendices as a "meeting reference". Additionally, written correspondence with Greenpeace Nordic/Copenhagen regarding CCUS feasibility in Denmark was also included in appendices as a "meeting reference". Additional valuable information could have been gained from conducting interviews with both AffaldVarme Aarhus and Greenpeace Nordic/Copenhagen.

Conclusion 8

In response to the growing threat posed by climate change, European governments are increasingly engaging with CCUS technologies in pursuit of ambitious national climate targets. In Denmark, CCUS is set to play a key role in reducing CO_2 emissions 70% compared to 1990s levels. However, previous efforts to deploy CCUS worldwide indicate the vulnerability of such projects to various factors impacting their feasibility, with a decline in the number of planned and operational CCUS projects observed over the last 10 years. Despite this, much of the debate in Denmark and across Europe remains focused on the techno-economic aspects of projects without considering the desirability of the technologies within society. Therefore, a broader set of factors impacting the feasibility of CCUS in Denmark was explored by answering the following research question:

How can international experiences around carbon capture, utilisation and storage be used to assess the feasibility of such projects in Denmark?

The study formulated and answered three sub-questions to guide the investigation and answer the research question. Each sub-question was dedicated to investigating factors and aspects relating to the feasibility of deploying CCUS projects, as well as the relative significance of these factors.

The first sub-question (chapter 4) was designed to identify barriers and enabling factors to CCUS projects in a global perspective. Through a comprehensive and systematic literature review of academic literature, supplemented by grey literature, a conceptual framework of 20 factors were identified and grouped into six categories comprising social, economic, technological, environmental, political and organisational (table 4.1). The results highlighted a focus within literature on how the social, economic and political categories impact CCUS feasibility, with particular interest around public perception, financial incentives and the cost of technology. Issues relating to technology readiness level and environmental risk were also shown to be important.

The second sub-question (chapter 5) built on the conceptual framework developed through literature by conducting a series of interviews with European practitioners in the field of CCUS. The framework became the focal point of the interviews, and the European practitioners were asked to reflect on their own experiences and the 20 factors. The results underscored the importance of social, economic and political factors and highlighted increased focus on business models, clusters and political support — factors not widely discussed in literature. Furthermore, European practitioners highlighted two factors absent from literature, namely industrial willingness and technological lock-in, which were mentioned by numerous interviewees. Additionally, the reflections from European practitioners provided an insight into how the progress of CCUS over the last decade has changed the significance of some factors. For example, the technological factors were predominantly highlighted as being an enabling force by the interviewees, compared to them being a barrier in literature. The main conclusion derived from interviews, is that the national context has an significant influence on the deployment of these technologies.

The third sub-question (chapter 6) explored the feasibility of CCUS in Denmark by applying the framework of barriers and enablers, developed using international experiences and literature, in relation to contextual data from Denmark. The results highlighted issues regarding the feasibility of CCUS in Denmark, with public perception (social), market incentives (economic) and a lack of clear policy (political) being key areas of continued uncertainty. Applying the framework of factors developed through chapters 4 and 5 therefore indicates that these issues need prioritising before CCUS developments in Denmark can progress effectively. In particular, technology lock-ins represent an key concern to the long-term feasibility of CCUS as a climate abatement mechanism, with potential lock-ins identified across numerous target industries.

Through an overall discussion the analysis highlights the influencing factors in a hierarchical framework, comprising a foundational (social, economic and political), optimisational (environmental and organisational) and physical implementation (technological) level. The framework is designed to to aid in the deployment of CCUS in Denmark, by highlighting which factors has been problematic in other countries.

Overall, international experiences from both literature and practitioners identified social, economic and political factors as key to the feasibility of CCUS projects. Failure to consider these on both a project and national level may result in projects halting before they get of the ground. Practitioner experiences also provided insight into how consideration and careful attention to these factors can stop them from being barriers, going so far as to highlight ways to turn them into enabling factors for the project. International experience also show that considering environmental factors is important for improving the overall feasibility of CCUS projects and increasing the environmental benefit of capturing CO_2. Furthermore, having broader considerations in terms of organisational factors can aid in decreasing the cost of infrastructure, thereby decreasing the cost per captured ton of CO_2 whilst ensuring that every stakeholder involved undertakes tasks within their area of competence. This is important in minimising the risk of technological failures (e.g. CO_2 leakage). The technological aspects of CCUS were ultimately highlighted by international experiences as being mature, and was therefore not considered a barrier. However, caution should still be taken, and the maturity of the technology should not be mistaken for its inability to fail or perform under expectation compared to alternatives.

International experiences underscore the fact that national, perhaps even regional, context is highly important in the deployment of CCUS. International experiences should therefore be viewed as a guideline in deploying CCUS rather than step-by-step template. Additionally, while the framework (figure 7.1) presents the factors in a hierarchy, all factors remain interrelated and influenced by one another in both positive and negative ways.

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Transparency in literature review A

Table A.1. Transparency overview showing the different categories and factors and their accompanying references.

Category	Factor	Publication
Social	Trust	1, 5, 9, 10, 19, 27, 28, 36, 46, 48, 55, 56, 58
	Public perception	1, 3, 4, 5, 6, 10, 11, 12, 14, 20, 26, 28, 40, 47, 51, 54, 58
	Cultural elements	47, 52, 56
	Knowledge	1, 7, 24, 28, 48, 49, 50, 54, 55, 58, 59, 61
Economic	Financial incentives	3, 6, 10, 11, 19, 23, 24, 30, 32, 49, 50, 51, 52, 53, 54, 55, 56, 58, 61
	Market incentives	3, 23, 31, 32, 40, 48, 51, 54, 56, 61
	Business model	15, 33, 34, 46, 58, 63
	Cost of technology	3, 4, 5, 6, 7, 13, 15, 32, 35, 41, 42, 46, 47, 48, 49, 51, 52, 54, 55, 58,
Technological	Technology readiness level	10, 27, 35, 40, 42, 47, 49, 54, 55, 56, 61
	Technology performance	13, 22, 26, 31, 33, 41, 47, 50, 55
	Infrastructure proximity	3, 4, 10, 17, 30, 31, 33, 41, 47, 50, 55
Environmental	Mitigation potential	4, 18, 26, 27, 42, 48
	Environmental risk	8, 10, 20, 33, 46, 48, 49, 51, 52, 53, 54, 58, 59
Political	Policy	4, 7, 19, 32, 46, 48, 49, 50, 56, 58, 61
	Regulation	8, 21, 34, 46, 49, 50, 51, 52, 53, 56, 59
	Legislative framework	3, 6, 17, 27, 28, 31, 34, 40, 46, 50
	Political support	10, 27, 36, 47, 55, 56
Organisational	Coordinating actors	10, 46, 47, 53, 56
	Coordinating activities	46, 55, 58, 59
	Clusters	17, 31

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B Overview of categories in the literature review

Table B.1. Overview of social factors impacting CCUS and related keywords as identified in the literature review.

Category	Factor	Keywords
Social	Trust	- Public trust - Trust in government / business - Global trust - Transparency - Confidence in technology - Government credibility - Public confidence
	Public perception	- Public perception - Public/social acceptance - Public acceptance of climate change - NIMBYism - Social support - Risk perception - Customer relations - Public concern
	Cultural elements	- Lifestyle - Path dependency - Behaviour - Diversity of memberstates
	Knowledge	- Knowledge - Education - Information - Technological and geological expertise - Guidance - Innovation - Research - Learning by doing - Broad understanding - Communication - Knowledge sharing - New insights - Public awareness - Feedback - Experiences

Table B.2. Overview of economic factors impacting CCUS and related keywords as identified in the literature review.

Category	Factor	Keywords
Economic	Financial incentives	- Research grants - Funding - Government funding - Subsidies - Financial support - Financial/economic incentives - Investment support (grant, tax credit, loan guarantee, subsidy by trust) - Incentives- Investment - Investment cost and uncertainties - Precautionary investments
	Market incentives	- Tax credit - Carbon price - Tax - CO2 price - EOR - Supply and demand - Income stream from profitable use of captured co2
	Business model	- Additional expenditure - Business model - Long-term liability - Feed-in tariff - Public-private partnerships - Revenue - Risk allocation
	Cost of technology	- Capital cost - Price/cost - Expensive - Cost-effectiveness - Affordability

Table B.3. Overview of technological factors impacting CCUS and related keywords as identified in the literature review.

Category	Factor	Keywords
Technological	Technology readiness level	- Utilisation - Technology readiness level - Technological maturity - Technological feasibility - Technically feasible and commercially defensible - Tests (demonstration projects) - Uncertainty of the technology - Technological lock-ins
	Technology performance	- Technology Performance - CO2 injection rate - Energy consumption - CO2 purity - Effectiveness
	Infrastructure proximity	- Storage capacity - Existing pipeline infrastructure - Technical requirements - Access - Suitability of storage sites

Table B.4. Overview of environmental factors impacting CCUS and related keywords as identified in the literature review

Category	Factor	Keywords
Environmental	Mitigation potential	- Mitigation potential - Life cycle emissions - Retention times - Capability of CO2 emission reductions - CO2 accounting methods
	Environmental risk	- Risks - CO2 leakage - Uncertainty - Health and Safety Risks (global and local) - Accidents - Public health - Impacts (public, environment)

Table B.5. Overview of political factors impacting CCUS and related keywords as identified in the literature review.

Category	Factor	Keywords
Political	Policy	- Strong policy - Policy - Clear policy - Policy support - Climate/energy policy - Climate policy concerns - Targets(goals) - Climate change negotiations - Agreement worldwide - Transboundary cooperation - International agreement - International collaboration (e.g., data sharing; joint research initiatives)
	Regulation	- Regulation - Regulatory framework - Compliance in regulation - Abundant regulations - Undeveloped regulatory and liability regimes - Permits - EIA - Monitoring
	Legislative framework	- Legislation - Legislative framework - Legal framework
	Political support	- Political support - Proactive - Ambition - Attention - Stakeholder engagement - Public encouragement - Responsibility - Customer relations - Lobbying

Table B.6. Overview of Organisational factors impacting CCUS and related keywords as identified in the literature review.

Category	Factor	Keywords
Organisational	Coordinating actors	- CCS promoters - Stakeholders - (E)NGO (e.g., Bellona) - Actor composition/network - Coordinating body (e.g., Gassnova)
	Coordinating activities	- CO2 Network - Collaboration - partnerships (national, international) - Holistic system thinking (Whole system) - Coordination activities - Planning - Structured and transparent process - Plans - Positive and supportive approach - Flexible/dynamic - Matching in expectation - Timescales/timeframe - Demonstration activities - Alliances with firms that have positive experience - (industrial) practice - Motivation
	Clusters	- Emissions cluster - Storage clusters

Interview guides C

C.1 First round of interview questions

General Introductions: *Welcome, we are...*

1. Would you like to start by elaborating on who you are and what you are working with in relation to **(your project)**?
2. What are your experiences with CCUS? (e.g. which parts of the process have you been involved with /)
   a) (Could you talk briefly about the different stages of the project so far (e.g. planning etc.))
      i. R&D, strategy and planning, project and financing, etc.
3. On which stage of the process would you currently place your project?

   Exploring influencing factors:
4. Up until this point in your project, what factors have had the greatest influence on the success of your project?
   a) Why, why, why?
   b) In which stage of the project lifecycle would you say these have the most influence?
   c) How did you/have you tried to manage or overcome these issues?

   After an initial discussion of the most influencing factors on CCUS deployment in their/your perspective, we present a figure C.1 illustrating the factors we identified through our literature review.
5. Follow up - remaining factors:)
   a) We identified additional factors:
      i. Social
      ii. Economical
      iii. Technology
      iv. Environmental
      v. Political
      vi. Organisational
   b) Do you have any experience of these?
      i. Which ones, and what are your experiences (apart from what you mentioned in the first part)?
      ii. If yes, in which stage of the project lifecycle would you say these have the most influence?
6. **If yes**, how did you/have you tried to manage or overcome these additional issues?
7. **If no**, where there something in particular you did in an effort to avoid these becoming obstacles?

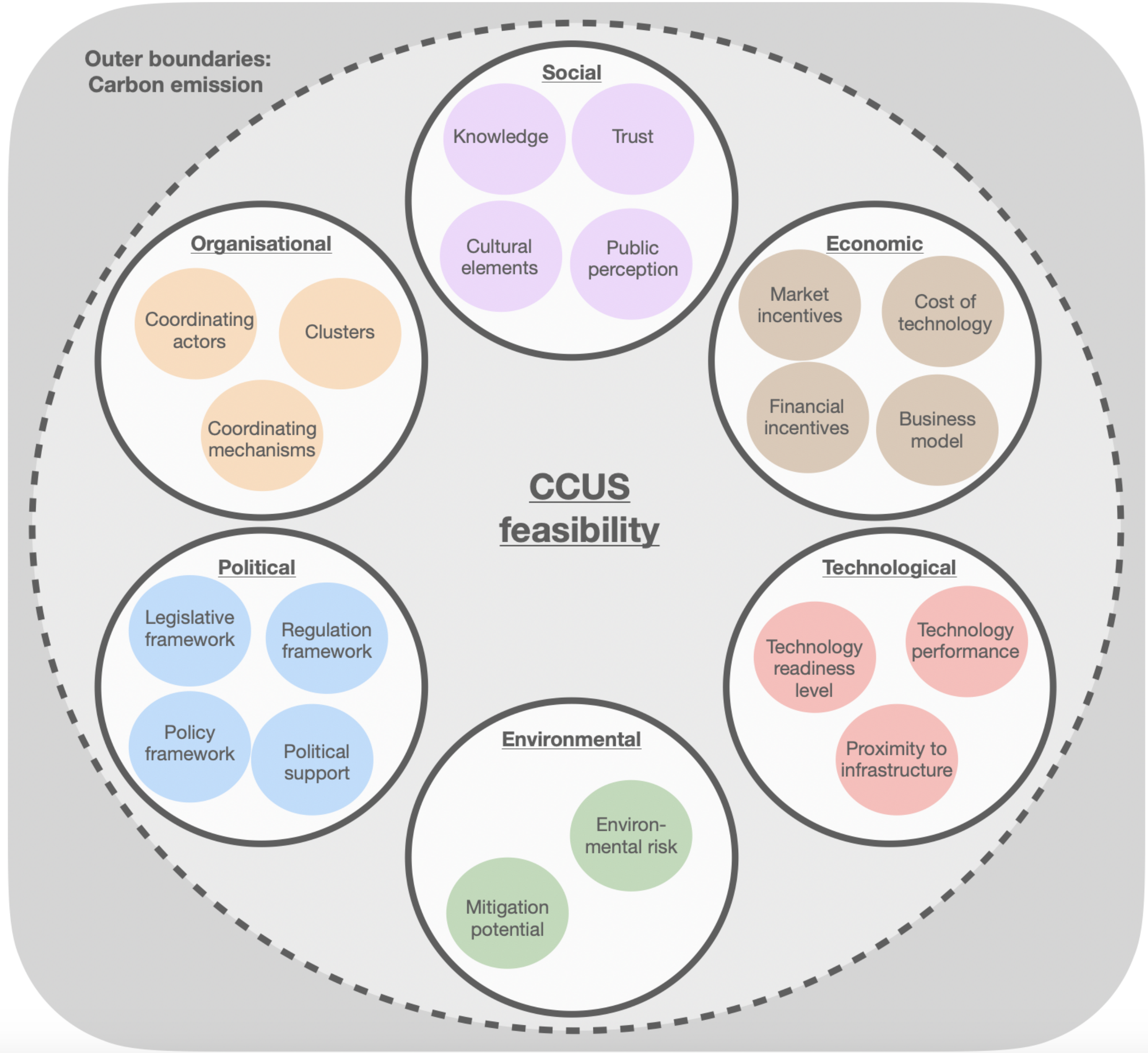

Figure C.1. Preliminary illustration of the conceptual framework of all 20 influencing factors divided into six categories, identified in literature. The illustration formed the basis for the co-creation part of the interviews.

C.2 Second round of interview questions

Welcome, we are...

1. Would you like to start by elaborating on who you are and what you are working with?
2. How do you see the feasibility and sustainability of CC from different sources of emissions in Denmark?
   a) Carbon capture from waste-to-energy plants
   b) Carbon capture from hard-to-abate industries
   c) Carbon capture from hydrocarbon refineries
   d) Carbon capture from biomass energy
   e) Alternatives
3. How do you see the feasibility and sustainability of the different transport solutions for Denmark?
   a) Transport by truck

   b) Transport by ship
   c) Transport by pipeline
   d) Alternatives
4. How do you see the feasibility and sustainability of onshore/offshore storage and utilisation in Denmark?
   a) Onshore storage
   b) Offshore storage
   c) Utilisation
   d) Alternatives
5. Do you see any alternatives to a technological solution for reaching Denmarks 2030 goals?

Transcriptions of first round interviews D

All the interview transcriptions are located at the supplementary appendices

D.1 Strategy CCUS

D.2 Longship (Gassnova)

D.3 Porthos

D.4 Acorn

D.5 C4

Transcriptions of second round interviews

E

All the interview transcriptions are located at the supplementary appendicies

E.1 DCCC (Klimarådet)

E.2 Arne Remmen

F Meeting references

All the meeting references are located at the supplementary appendices

F.1 AffaldVarme Aarhus

F.2 Greenpeace Nordic/CPH