Klima-, Energi- og Forsyningsudvalget 2022-23 (2. samling)
KEF Alm.del - Bilag 130
Offentligt

ASSESSMENT OF THE MARKET POTENTIAL FOR CO2 STORAGE IN DENMARK

ENERGISTYRELSEN

MAY 2021

RAMBOLL Bright ideas. Sustainable change.

CONTENTS

1.	**BACKGROUND AND INTRODUCTION**	**4**
2.	**DANISH ABSTRACT**	**6**
3.	**EXECUTIVE SUMMARY**	**11**
4.	**CCS MARKET POTENTIAL**	**16**
4.1	KEY CONCLUSIONS ON THE CCS POTENTIAL IN NORTHERN EUROPE	16
4.2	COUNTRY DEEP-DIVES	18
4.3	ASSUMPTIONS UNDERLYING ESTIMATION OF CAPTURABLE CO2	65
5.	**OVERVIEW AND EVALUATION OF POTENTIAL SET-UPS FOR TRANSPORT AND STORAGE OF CO2 IN DENMARK**	**69**
5.1	KEY CONCLUSIONS ON THE POTENTIAL SET-UPS FOR TRANSPORT AND STORAGE OF CO2 IN DENMARK	69
5.2	MAPPING OF NORTH EUROPEAN CO2 STREAMS RELEVANT FOR DANISH STORAGE	70
5.3	POSSIBLE SET-UPS FOR TRANSPORT AND STORAGE OF CO2 IN DENMARK	73
5.4	ASSESSMENT OF DANISH COMPETITIVENESS FOR CO2 STORAGE	83
5.5	INSTITUTIONAL CONSIDERATIONS	84
6.	**PROFITABILITY ASSESSMENT OF CO2 STORAGE IN DENMARK**	**93**
6.1	INTRODUCTION TO BUSINESS CASES	93
6.2	OVERVIEW OF ANALYSED BUSINESS MODELS	95
6.3	BUSINESS CASE ASSUMPTIONS	96
6.4	KEY CONCLUSIONS ON THE PROFITABILITY OF THE CO2 STORAGE IN DENMARK	98
6.5	BUSINESS CASE DEEP-DIVES	102
6.6	BUSINESS CASE PREREQUISITES	106
6.7	PRO’S AND CON’S FOR THE ASSESSED BUSINESS CASES	108
7.	**APPENDIX**	**109**
7.1	GRAPHICAL OVERVIEW OF BUSINESS MODEL SET-UPS	109
7.2	GRAPHICAL OVERVIEW OF BUSINESS CASES	113
7.3	OVERVIEW OF COSTS AND ASSUMPTIONS PER BUSINESS MODEL SET-UP	116
7.4	OVERVIEW OF ESTIMATED CCS SHARE BY COUNTRY	147

ABBREVIATONS

Abbreviation	Explanation
AC	Active current
BECCS	Bio-energy carbon capture
CAPEX	Captial expenditures
CCC	Climate change committee (UK)
CCS	Carbon capture and storage
CCU	Carbon capture and utilisation
CCUS	Carbon capture utilisation and storage
CfD	Contract for difference
CO2	Carbon dioxide
CPH	Co-generator of power and heat
DK	Denmark
EE	Estonia
FSU	Floating storage unit
GHG	Greenhouse gas
HFO	Heavy fuel oil
IPCC	International panel of climate change
IRR	Internal rate of return
km	kilometre
LNG	Liquid natural gas
LT	Lithuania
LULUCF	Land-use, land-use change and forestry
LV	Latvia
MSW	Municipal solid waste
Mt	Megaton (1,000 ton)
MtCO2/y	Megaton carbon dioxide per year
MtCO2e	Megaton carbon dioxide equivalent
NL	The Netherlands
NO	Norway
NPV	Net present value
OPEX	Operational expenditures
PL	Poland
Pre-FID	Pre-finale investment decision
SDE++	Stimulation of sustainable energy production
T&S	Transport and storage
UK	United Kingdom

1. BACKGROUND AND INTRODUCTION

Ramboll has been commissioned by The Danish Energy Agency to conduct market study of transport and storage of CO2 in Northern Europe, which will impact the extent to which CCS-capacity will be planned and developed in Denmark. The report assesses whether and to what extent there is market potential for storing CO2 exports from Northern European countries in Denmark as well as Denmark's competitiveness in being a potential European CO2 storage provider. Possible set-ups for transporting and storing CO2 in Denmark from countries deemed to have highest potential to export CO2 to Denmark are mapped to identify a selection of market-based (i.e. relevant and competitive; hereunder, cost-effective and convenient transport and storage solution for emitters) business case set-ups. An important distinction is made between business case set-ups and business models. Business case set-ups bring forth the most relevant market-based cases for which the profitability and break-even is calculated, whereas business models incorporate the organisational aspects; In this case, pivotal institutional considerations necessary to develop transport and storage infrastructure and operate it. Institutional considerations are discussed to highlight the need for state- and Government's involvement, as without it, the development of CCS solutions will not be likely since private players are not incentivised at present to establish CCS themselves. The report culminates in the presentation of selected competitive business case set-ups, including their expected profitability and a discussion of their underlying prerequisites, e.g., the necessary institutional prerequisites to achieve the estimated business case results and the advantages and disadvantages of each case.

Background

The Intergovernmental Panel on Climate Change (IPCC) has stated that carbon removal technologies will be needed to reach the climate goals set in the Paris agreement, limiting global warming to 1.5C by 2100. Carbon capture and storage (CCS) has been highlighted as an essential means to remove CO2[1].

Although there is a significant potential for CCS technologies, a well-established market does not yet exist in Northern Europe. The most advanced CO2 storage developments are not expected until the end of 2024.

In Denmark, both GEUS and The Danish Energy Agency have amongst others been proponents of CCS technology, but it was not until 2020 that CCS was discussed at the political level. Additionally, the Danish Waste Association published a memorandum in 2019, in which CCS was a pivotal part of the vision for a CO2-neutral waste sector. In 2020, the climate agreement for industry and energy ("Klimaaftalen for Industri og Energi m.v. af 22. juni 2020") was signed, stating that funding will be allocated and increased towards 2029 for market-based CCS or similar technologies, which have the aim to reduce CO2 in the atmosphere[2].

Denmark possesses many suitable reservoirs in the subsoil for storing CO2, and the Danish Energy Agency wants to be well-equipped to prepare a CCS strategy to position themselves in this emerging market. To do this, they need to understand the market for CCS, the potentials and particularly Denmark's competitiveness in the market.

As such, Ramboll has been requested to investigate the market potential for CO2 storage from Northern Europe in Denmark, an assessment of Denmark's competitiveness in this market and associated market-based business case set-ups, including the necessary prerequisites. The results of the investigating will indicate and have an impact on the extent to which CCS capacity will be planned in Denmark.

Introduction

The report is structured into three main chapters ("CCS potential", "Overview and evaluation of possible set-ups for transport and storage of CO2 in Denmark" and "Profitability assessment of CO2 storage in Denmark"), that investigates the following topics:

- Potential for CCS and exports to Denmark from ten selected Northern European countries (UK, Norway, Sweden, Finland, Poland, Estonia, Latvia Lithuania, The Netherlands and Germany);
- Mapping of possible set-ups for transport and storage of CO2 and their associated costs;
- Institutional considerations for a CCS business model in Denmark;

[1] BBC – The device that reverses CO2 emissions

[2] Regeringen - Klimaaftale for energi og industri mv. 2020

- Assessment of Denmark's competitiveness as a CO2 storage provider; and
- A business case evaluation of business case set-ups where Denmark is deemed to have a competitive advantage

CCS market potential

The aim of this assessment is to provide a thorough understanding of the market potential for CCS in the Northern European countries covered in this analysis, with a particular emphasis on identifying import opportunities, specified as the share of capturable CO2 intended for storage, that cannot be stored within the country's own CO2 storage capacity. Thus, the assessment covers estimated CCS potential within each of the ten analysed counties, the CO2 storage capacity, and, on this basis, a potential gap for the country's need to export CO2 to be stored abroad is found. The assessment will, in this sense, provide input to the volumes used in the business cases.

Overview and evaluation of possible set-ups for transport and storage of CO2 in Denmark

Potential set-ups for storage and transport are assessed to outline various options that are possible for transport and storage of CO2, as well as to calculate the costs and compare them between the options. This to identify relevant market-based business case set-ups, which are cost-efficient and where Denmark can be competitive. The input from this assessment is applied when constructing the business cases and the associated cost inputs.

This part of the analysis also discusses institutional considerations, which are important to consider in a CCS business model since there is a need for state and Government involvement as well as a mix of various bodies to establish the CCS infrastructure and operate the business. The input from this assessment will serve as some of the prerequisites for the business case set-ups in the following chapter.

Profitability assessment of CO2 storage in Denmark

This part of the analysis provides a view on whether and when selected business case set-ups will be profitable and under which pre-requisites. The business cases are chosen based on the previous analyses, which indicate potential set-ups where Denmark is competitive. These business cases will provide decision-making material for the Danish Energy Agency who will compare the different business cases.

2. DANISH ABSTRACT

CCS markedspotentiale

Den politiske opbakning til CCS varierer meget imellem de ti lande, denne analyse omfatter (Finland, Sverige, Norge, Tyskland, Storbritannien, Holland, Polen, Estland, Letland og Litauen). De lande, hvis **nationalpolitik er mest imødekommende over for CCS, er Norge og Storbritannien**. Begge har stærke støtteordninger for CCS, der målrettet udvikler teknologien og understøtter projekter, som sænker omkostningerne for CCS. Desuden har landene udviklet fordelagtige lovgivningsmæssige rammer og konkrete CCS-mål eller forpligtelser, der er fremsat med henblik på at implementere CCS på nationalt plan. De lande, hvis **nationalpolitik er mindst imødekommende over for CCS, er Polen og de baltiske lande** (Litauen, Letland og Estland). Ingen af disse har inkluderet CCS som en del af deres nuværende klimastrategi eller foreslået støtteordninger, lovgivning eller konkrete mål med henblik på at udvikle eller implementere CCS teknologi på nationalt plan. Imidlertid har disse lande anerkendt, at CCS teknologien potentielt kan blive relevant i fremtiden, hvilket indikerer en voksende politisk interesse for emnet.

De lande (som analysen behandler) med **den største CO2 udledning fra store kilder** er Tyskland, Polen, Storbritannien og Holland. I 2017 havde de en udledning på hhv. MTCO2 ~406, ~166. ~146, and ~95. Af disse lande anses **Storbritannien, Tyskland og Polen for at have de største totale CCS-potentialer**. I Tyskland og Polen kan den største del af CCS-potentialet tilskrives fossile kraftværker, hvor det i Storbritannien kan tilskrives både kraft- og varmesektoren samt de CO2-tunge industrier (olie og gas raffinaderier, mineral-, jern og stål-, kemikalie- og madvareproducenter). **Det totale CCS-potentiale i Sverige, Finland** (i begge tilfælde tilskrives det hovedsageligt papirmasse- og papirindustrien) **og Holland** (tilskrives det en kombination af både naturgasværker og de CO2-tunge industreri) **er vurderet til at være forholdsvis mindre relevant**. Derudover er CCS-potentialet i de baltiske lande vurderet til at være ubetydeligt. I denne sammenhæng grundet deres relativt lave CCS volumener.

Både **Storbritannien og Norge har høje ambitioner for national CO2 lagring** (og endda for import af CO2 fra udlandet), hvor Tyskland, Polen og Sverige er mere tilbageholdende overfor national lagring af CO2. Lagringskapaciteten i de baltiske lande anses desuden for at være uegnet til CO2 lagring.

Tyskland, Sverige og Finland anses for at have det største potentiale for at eksportere CO2 (med henblik på lagring) til Danmark, hvor **Holland og Polens anses for at være af sekundær karakter.** Storbritannien og Norge er de vigtigste konkurrenter for Danmark ift. disse Nordeuropæiske CO2- strømme. CCS-potentialet i Baltikum (Estland, Litauen og Letland) er så lavt, at det anses som værende ubetydeligt.

Overblik og evaluering af mulige set-ups for transport og lagring af CO2 i Danmark

De vejledende **CO2-volumener, som er relevante for danske CO2-lagre (inklusiv de nationale CO2 volumener), er vurderet til at være op imod ~45 MtCO2/år**. For de danske lagre anses import af CO2 fra Tyskland, Sverige og Finland som værende mest relevant. Import af CO2 fra Holland og Polen har også betydning for dem, men er vurderet til at være i relativt mindre volumener og tilskrives større usikkerhed. CO2-import fra Baltikum, Norge og Storbritannien forventes desuden at være af ubetydelig størrelse (de to sidstnævnte lande har veludviklede nationale lagringsprojekter).

Danmarks potentielt bedste lagringsmuligheder ligger i Havnsø (onshore), Gassum (onshore), Hanstholm (nearshore) og i den nordlige del af de danske olie- og gasfelter i Nordsøen. Transportmuligheder inkluderer tankskibe, fartøjer og rørledninger. Udenlandske lagre, der potentielt kan konkurrere med danske lagre, er fortrinsvist placeret i Norge eller Storbritannien.

For at sammenligne omkostningerne for forskellige sammensætninger af CO2 transport- og lagringsmuligheder er ni mulige set-ups opstillet. Dette er blevet gjort med henblik på at vurdere deres konkurrencedygtighed individuelt såvel som i kombination. De ni opsætninger inkluderer en række kombinationer af transport og lagringsmuligheder, hvilket betyder, at nogle opsætninger har behov for havne med mellem-lagringsmuligheder, mens andre ikke har. Rambøll har desuden vurderet, at det ikke er muligt at håndtere 45 MtCO2/år ved anvendelse af ét enkelt danske lager, hvilket betyder, at hvis en lagringskapacitet på 45 MtCO2/y er ønsket, er en kombination af de opstillede set-ups nødvendigt.

Table 1: Enhedsomkostninger (DKK/t) for hvert set-up ved 5 MtCO2/år (bestående af transport og lager; CAPEX, akkumuleret OPEX og nedluknings omkostninger)

Set-up	#1	#2	#3	#4	#5	#6	#7	#8	#9
	Onshore; Tankskib -> havn -> lager via rørledning	**Onshore**; Tankskib & rørledning (fra KBH) -> havn -> lager via rørledning	**Nearshore;** Tankskib -> havn -> lager via rørledning	**Nearshore;** Tankskib & rørledning (fra KBH) -> havn -> lager via pipeline	**Offshore,** Tankskib -> havn -> lager via rørledning	**Offshore,** Fartøjer -> CO2 lager	**Offshore,** Tankskib -> permanent tøjret FSU -> CO2 lager	**Offshore,** Tankskib & rørledning (fra DE) -> havn -> lager via rørledning	**Offshore,** Tankskib (SE, FI, PL & DK) -> havn -> lager via rørledning + rørledning (fra NL & DE) -> lager
DKK/t	106	91	136	133	175	207	185	166	221

Bemærk: Enhedsomkostninger præsenteret ovenfor er vist som dagens priser og ekskl. forrentning (ikke levelised)

Generelt viser omkostningssammenligningerne, at **onshore lagre generelt er de mest omkostningseffektive** (uafhængigt af transportløsningen), **efterfulgt af nearshore lagre**, og med offshore lagre som den dyreste løsning. Desuden, **giver rørledninger skaleringsfordele, hvilket betyder, at det er den mest omkostningseffektive transportløsning ved stor skala.**

Alle lagertyper og transportløsninger har fordele og ulemper udover deres respektive omkostningseffektivitet. Udover at være den billigste løsning, **har onshore lagret i Havnsø også den fordel at være placeret tæt ved store nationale CO2 kilder** (fra Københavnsområdet). Det er desuden usikkert, om lageret overhovedet kan anvendes (hvilket understreger vigtigheden af at udføre forundersøgelser i form af seismiske test og boringer), og den generelle **risiko for modstand fra offentligheden,** som kan lede til en forlænget godkendelsesproces sammenlignet med offshore lagre.

Selvom offshore lagerløsningen er den dyreste løsning, har den en række fordele, især i form af at **man ved at det praktisk muligt at etablere lageret.** Desuden er tæthedsgraden for de geologiske strukturer veldokumenteret, hvilket betyder, at det muligvis er **nemmere at få de nødvendige tilladelser** til at etablere lageret (især sammenlignet med onshore løsningen). Desuden kan noget af det **eksisterende udstyr** (i form af platforme og hjælpesystemer) **potentielt genanvendes** eller eftermonteres. Dermed har offshore lagret **potentiale for at være tidligere klar,** end onshore og nearshore løsninger.

Set-ups, der inkluderer rørledninger fra Tyskland, vil formentligt resultere i mere stabile og pålidelige CO2-volumener fra udlandet, hvilket muligvis vil gøre det nemmere (og billigere) at finde investorer. Denne type transportløsning giver kun mening når et set-up på stor skala planlægges fra starten. Set-ups baseret på skibstransport muliggør derimod en start ved mindre skala og muliggør derefter en gradvis udbygning efter behov. Bemærk, at gradvis udbygning også er muligt for onshore lageret, hvor efterfølgende etablering af rørledninger fra udledningskilder eller anden tilhørende infrastruktur også er muligt.

Dansk konkurrenceevne for CO2-lagring vurderes på baggrund af følgende kriterier for konkurrencedygtighed: løsningen er omkostningseffektivt, har lave marginalomkostninger og inkluderer muligheden for at indbygge fleksibilitet for kunden. Ud fra dette har Rambøll vurderet, at **Danmark kan tilbyde en konkurrencedygtig løsning, som er både omkostningseffektiv, fleksibelt og praktisk for de mest relevante lande (især Tyskland, Sverige, Finland og potentielt Polen)**. De mest omkostningseffektive løsninger er baseret på set-ups, hvor store mængder CO2 transporteres gennem rørledninger og efterfølgende lagres i onshore eller nearshore lagre.

Institutionelle overvejelser har ledt til disse tre key take-aways:

- Det er nødvendigt med **statslig indblanding** ift. finansiering (af forudbetalte kapitalomkostninger), risikostyring og støtte af CCS initiativer/projekter, da markedsspillere på nuværende tidspunkt hverken har kapaciteten eller økonomisk incitament til at udvikle CCS teknologi. Dermed er der stor sandsynlighed for at støtte og aktiv involvering fra den danske stat og regering vil blive nødvendigt

- Der er et behov for, at der **involveres en organisation, der på vegne af staten administrerer og bevarer et strategisk overblik** over projektet, og som sikrer at projektet forløber i overensstemmelse med planen, samt at incitamentsstrukturen effektivt demonstrerer markedsbaseret succes
- Det er nødvendigt, at en eller flere af de deltagerende parter har **operationel og teknisk ekspertise** til at drive forretningen

Rentabilitetsvurdering af CO2-lagring i Danmark

Baseret på Rambølls vurdering af Danmarks strategiske konkurrencefordele fremgår tre typer forretningsmodeller som værende de mest konkurrencedygtige.

Table 2: Overblik over forretningsmodeller

Case 1 & 2: Danmark kommer primært til at være en national CO2-lagringsudbyder på lille-til-mellemstor skala og bliver en mindre spiller på det internationale marked	**Case 3:** Danmark etablerer sig selv som en stor international CO2-lagringsudbyder samtidig med, at det nationale markedsbehov også imødekommes
I dette tilfælde lagrer Danmark hhv. 5 MtCO2/y (case 1) eller 10 MtCO2/år (case 2) og fokuserer primært på de nationale CO2 volumener; **Der er tre forskellige lagertyper, som kan anvendes i disse tilfælde:** • **1) Offshore lagring på lille skala med skibstransport til Nordsø-felterne,** hvor fartøjer transporterer CO2 primært fra kilder i Danmark direkte til Nordsø-felterne, hvor det bliver lagret • **2a): Onshore lagring på mellemstor skala i Havnsø**, rørledningstransport fra København, og skibstransport fra andre kilder • **2B): Nearshore lagring på mellemstor skala i Hanstholm**, rørledningstransport fra København og skibstransport fra andre kilder • **2C): Offshore lagring på mellemstor skala i Nordsø-felterne**, rørledningstransport fra København til Esbjerg og skibstransport fra forskellige CO2-kilder til Esbjerg (som er forbundet til offshore lageret via en rørledning) **Bemærk, at løsninger på lille skala også kan udvikles for hhv. onshore og nearshore lagre, hvor begge disse lagertyper muligvis kan være mere fordelagtige hvis sammenlignet med offshore løsningen i case 1. imidlertid omfatter denne rapport kun beregninger af omkostningerne for offshore lagre ved lille skala.*	I dette tilfælde udbyder Danmark lagring af CO2 på en stor-skala for det internationale marked. Danmark har en geografisk konkurrencefordel i form af at være strategisk tæt placeret på Tyskland – Europas størst CO2 udleder – Sverige, Finland, Polen og Holland. Danmark har desuden mulighed for at tilbyde attraktive og omkostningseffektive rørledningsløsninger til tyske CO2-volumener; rørledningen ville gå fra Nordtyskland til Esbjerg og have en kapacitet på 20 MtCO2/år. I alt vil Danmark lagre 40 MtCO2/år; 20 MtCO2/år fra Tyskland, 15 MtCO2/år fra Sverige, Finland og Polen samt 5 MtCO2/år fra nationale kilder. Denne case forudsætter involvering i det internationale CO2-lagringsmarked og anses som værende i stor skala, hvilket betyder, at denne case har en mere udbredt CO2 transport- og lagringsinfrastruktur ift. case 1 & 2, fordi flere lagrings- og transportløsninger kombineres med henblik på at opnå den ønskede skala og dermed mere effektiv udnyttelse af driftsaktiver.

Table 3: Enhedsomkostninger (DKK/tCO2) for hver underliggende forretningsmodel (bestående af transport og lager; CAPEX, akkumuleret OPEX og nedluknings omkostninger)

	Case 1 (5 MtCO2/y)	**Case 2A** (10 MtCO2/y)	**Case 2B** (10 MtCO2/y)	**Case 2C** (10 MtCO2/y)	**Case 3** (10 MtCO2/y)
DKK/t	172	82	109	132	101
NPV	-2.0 BDKK	11.5 BDKK	5.5 BDKK	2.1 BDKK	26.6 BDKK
IRR	0.2%	12%	7%	5%	9%

Bemærk: Enhedsomkostninger præsenteret ovenfor er vist som dagens priser og ekskl. forrentning (ikke levelised)

Fire ud af fem cases har en positiv NPV (nettonutidsværdi) inden for deres 30-årige livstid og har en tilbagebetalingsperiode på 8-25 år. **Det er vigtigt at bemærke, at de ovennævnte forretningsmodeller tager udgangspunkt i en antagelse om, at der vil være forretning i at udbyde CO2 lagerplads, og at prisen vil være en kombination af f.eks. CO2 priser, CO2 skatter, bevillinger, etc.** Imidlertid anses det ikke for at være nødvendigt at kende den præcise sammensætning af CO2 lagringssubsidierne for at kunne vurdere rentabiliteten og break-even for de ovennævnte cases. Tværtimod er det vigtigere at kunne estimere en repræsentativ pris for CO2 transport- og lagring baseret på et plausibelt markedsbaseret (og dermed konkurrencedygtigt) scenarie. Derfor har Rambøll udviklet en referencepris, der er baseret på de omkostninger et Nordeuropæisk land ville have i forbindelse med eksport af CO2 til et offshore lager i Storbritannien. Dette anses som værende repræsentativt for et muligt alternativ til de danske CO2-lagringsløsninger. Referenceprisen er baseret på et gennemsnit af omkostninger for en række af danske offshore lagerløsninger, som fremgår i set-ups (kapitel 5.3). Desuden er anvendelsen af en referencepris anset som værende den mest repræsentative forudsigelsesmetode, eftersom forudsiger af CO2-priser og støttemekanismer indebærer høj usikkerhed og en række uforudsigelige sammensætningsmuligheder (f.eks. usikkerhed omkring indkomst fra CO2-priser, skatter og bevillinger, allokeres eftersom den indkomst ikke udelukkende går til transport- og lagringsudbyderne i CCS værdikæden).

Forretningsmodellen med den højeste **NPV; DKK ~26.6 milliarder, er case 3** (stor-skala international CO2 lagringsløsning), primært baseret på høje årlige omsætningsvolumener (40 MtCO2/år) og stordriftsfordele, der kommer til udtryk via effektiv udnyttelse af driftsaktiver samt integration af transport- og lagerløsninger med synergi, f.eks. rørledninger, der bliver anvendt som transport til flere lagre. Desuden anvendes alle lagertyper i denne case, hvilket betyder CAPEX er lavere sammenlignet med udelukkende at anvende offshore lagre. Selvom case 3 har væsentligt højere totale omkostninger, end de nationalt fokuserede cases, forventes tilbagebetalingsperioden (**på 11 år)** at være kortere end case 1, 2B og 2C. Dette skyldes som førnævnt de høje omsætningsvolumener kombineret med stordriftsfordele/ udnyttelse af omkostningseffektive lager- og transportløsningerne.

Selvom case 1 (offshore CO2 lagring udelukkende med direkte skibstransport) **har tydelige fordele i form af fleksibilitet, giver case 1 en negativ NPV på DKK ~(2.0) milliarder** og **den længste tilbagebetalingsperiode (25 år)**. Dette skyldes primært OPEX omkostningerne for denne case, som er betydeligt højere, end de andre nationaltfokuserede cases. Bemærk, at denne case forudsætter, at CO2 udelukkende transporteres med fartøjer (den dyreste transportløsning) igennem hele projektets 30-årige livstid. Hvis transportløsningen blev optimeret i løbet af projektets levetid, ved f.eks. at udbygge med en rørledning eller en permanent FSU, kunne forretningsmodellen i denne case potentielt forbedres. Desuden medfører den generelle usikkerhed omkring omsætning en del usikkerhed i case beregninger. Rentabiliteten for denne case ville forbedres, hvis omsætningen er højre end antaget for business cases i denne rapport.

Case 2C (mellemstor skala, nationalt fokuseret case med offshore lager), giver en **NPV på DKK ~2.1 milliarder** og en **tilbagebetalingstid på 15 år**. Selvom NPV er positiv for denne case, er den dyrere end 2A og 2B, eftersom offshore lagerløsninger har højere omkostninger, end onshore og nearshore løsninger.

Case 2A (mellemstor skala, national fokuseret case med onshore lager), **har den anden højeste NPV på DKK ~11.5 milliarder** og den **korteste tilbagebetalingstid (8 år)**. **Case 2B** (mellemstor skala, nationalt fokuseret case med nearshore lager) har en **NPV på DKK ~5.5 milliarder og en tilbagebetalingstid på 13 år**. Den case har den højeste CAPEX og den anden højeste OPEX af all mellemstore cases (2A, 2B og 2C).

De ovenstående resultater er baseret på en række forudsætninger, som bl.a. inkluderer størrelsen af de forventede CO2-volumener, effektiv projektledelse, identificering af kvalificerede parter med henblik på at give ansvar for projektets implementering, finansiel støtte (både national og for case 3 også international), at de nødvendige tilladelser tildeles uden store forsinkelser, at teknologien fortsat forbedres, og at det er muligt at begynde drift senest i 2030 (i det mindste på linje med den forventede hastighed på udbygningen af den årlig lagringskapacitet). Desuden har nogle cases specifikke forudsætninger, f.eks. at de udvalgte lagre (især de mindre kendte onshore og nearshore lagre) kan anvendes til lagring af CO2, og at adgang til den pågældende offshore rørledningsinfrastruktur er godkendt før anlægsarbejdets begyndelse (og at det er muligt at eftermontere rørledningen til at håndtere store CO2-volumener), samt at de nødvendige internationale aftaler er indgået på forhånd, f.eks. en aftale med tyske firmaer og stat om eksport af CO2-volumener.

Desuden er **fordelene og ulemperne** for både case 1 & 2 (national løsning) og case 3 (international løsning) blevet **opstillet og sammenlignet** nedenfor.

Her er det vigtigt at bemærke, at nationalt orienterede løsninger er mindre komplekse og billigere (især case 2A har en konkurrencedygtig pris, den højeste IRR og den korteste tilbagebetalingsperiode). Imidlertid kan det være svært, når man starter på mindre skala, efterfølgende at udvide til større skala med fokus på internationale markedsløsninger sammenlignet med at planlægge efter stor skala fra begyndelsen. Bemærk, at for den nationalt fokuserede case i lille skala med fartøj transport (case 1), har den største grad af fleksibilitet. Det betyder, at der er mulighed for efterfølgende at udbygge til mellemstor skala (og endda stor skala, selvom denne form for udbygning til stor skala kan betyde tabt omsætning og spildte muligheder) og modificere til trinvis udvidelse. Dermed giver denne case mulighed for at udforske markedet og udskyde den endelige beslutning for den strategiske retning for projektet. Case 1 har dog de højeste enhedsomkostninger (DKK/tCO2).

Den internationalt orienterede løsning (case 3) muliggør fuld udnyttelse af markedspotentialet (og Danmarks strategiske placering tæt ved Tyskland, Sverige, Finland og Polen), ved at tilbyde en konkurrencedygtig, praktisk og potentielt bindende løsning. Denne løsning har også potentiale til at blive en del af EU's ambitiøse plan for CO2 reduktionsmål, og dermed sikrer international finansiering og risiko-/omkostningsdeling. Denne løsning er kompleks (dog ikke urealistisk, som senest vist ved etableringen af Baltic Pipe), hvor det blev demonstreret, at det er nødvendigt med meget statslig indblanding og investering. Det samme gælder, hvis en udbredt CCS-infrastruktur skal etableres. Dette ville også kræve EU's samarbejde ift. at få finansiel støtte samt hjælp til implementering af politik, der kan bidrage til at etablere et internationalt CO2 lagringsmarked. Desuden har denne løsning mere gennemslagskraft ved en eventuel forhandling, hvis den er planlagt til at være i stor skala fra begyndelsen – efterfølgende tilføjelse af ekstra lagre og infrastruktur kan have en negativ effekt på konkurrencedygtigheden af dette system samt størrelsen af de forventede CO2-volumener.

Refleksioner og anbefalinger til fremadrettet arbejde

Ud fra de vurderinger der er blevet præsenteret i rapporten og anbefalingerne til det fremadrettede planlægningsarbejde af CO2 lageringsløsninger i Danmark, er det nødvendigt at:

- **Beslutte om import af udenlandsk CO2 er ønsket**
- **Kortlægge realistiske lagerløsninger** baseret på interne præferencer og ambitioner. Dette skal opfølges med en vurdering af, om der er et økonomisk optimeringspotentiale udover de præsenterede løsninger i denne rapport (f.eks. ved store-til-middelstore løsninger)
- **Igangsætte forundersøgelser** af de potentielle lagre, med henblik på at få en fuld forståelse for deres potentiale og begrænsninger. Dette vil gavne og potentielt fremskynde godkendelsesprocessen, eftersom mere anerkendt data kan undersøges og dermed begrænse usikkerheder og risici
- Hvis ambitionen er, at Danmark etableres som en international CO2-lagringsudbyder, er det nødvendigt at **påbegynde strategiske partnerskaber og samarbejder (især med tyske stakeholders) snarest muligt**. Lignende partnerskaber findes inden for vindenergisektoren – f.eks. North Sea Wind Power Hub, som er et konsortium mellem Energinet, Gasunie og TenneT, som sammen faciliterer en accelereret implementering af offshore vindenergi i Nordsøen. Dette partnerskab kan anvedes som inspiration.

3. EXECUTIVE SUMMARY

CCS market potential

The political support for CCS varies considerably among the ten analysed countries (Finland, Sweden, Norway, Germany, UK, the Netherlands, Poland, Estonia, Latvia and Lithuania). The **countries with the most favourable national policies are Norway and UK**, both of which have strong policies aimed at CCS, support schemes aimed at advancing the technology and projects to drive down costs, favourable regulatory CCS frameworks as well as targets or commitments towards its deployment. The **countries with the least national focus on CCS include Poland and the Baltic countries** (i.e., Lithuania, Latvia, and Estonia) since none of the countries currently pursue CCS as a strategy to reach climate targets, i.e. there no supporting policies, funding schemes, regulation or targets in place to enhance CCS deployment. However, even these lowest ranking countries have acknowledged that CCS might potentially be relevant in the future, which may indicate growing political interest in the topic.

Among the analysed countries, the **highest emissions levels** from large sources are found in Germany, Poland, UK, and the Netherlands, with MtCO2 emissions in 2017 at ~406, ~166, ~146, and ~95, respectively. Concerning CCS potential, the report assesses that **UK, Germany, and Poland demonstrate the highest total capturable volumes intended for CCS** among the analysed countries. In Germany and Poland, a large share of CCS potential is linked to fossil power plants. In contrast, in UK the CCS potential is linked to both the power & heat sector and hard-to-abate industries (mineral oil & gas refineries, minerals, iron and steel, chemicals and food). **CCS potential is also assessed in Sweden, Finland** (in both cases mainly related to the pulp & paper industry), **and the Netherlands** (a combination of natural gas plants and industry). The CCS potential in the Baltic countries is assessed to be insignificant due to low volumes.

Both **UK and Norway have high ambitions for domestic storage** (and even import of CO2 from abroad), while Germany, Poland and Sweden are more reluctant to domestic store CO2. No suitable storage capacity is assessed in the Baltic region.

Germany, Sweden and Finland are deemed to have the most potential to export CO2 to Denmark with the intention of carbon storage. In contrast, the **Netherlands and Poland have secondary potential**. UK and Norway are the major competing countries for CO2 streams in Northern Europe. The potential in the Baltics (Estonia, Lithuania and Latvia) have such small amounts of CCS volumes, and thus, the potential is almost insignificant.

Overview and evaluation of possible set-ups for transport and storage of CO2 in Denmark

The indicative CO2 **volumes relevant for storage in Denmark (including domestic CO2 volumes) are estimated at up to ~45 MtCO2/y**. Import of CO2 for storage in Denmark is mainly relevant from DE, SE and FI. However, lower and more uncertain potential for CO2 import is also assessed from PL and NL, while no or insignificant import is expected from the Baltics, NO or UK (the latter two have well-developed domestic storage projects).

Available options for storage are Havnsø (onshore), Gassum (onshore), Hanstholm (nearshore) and the Northern oil and gas fields in the North Sea (offshore). Available options for transport are shuttle tankers, vessels, and pipelines. The foreign storages that could potentially compete with the Danish CO2 storages are mainly UK and Norway.

Nine different set-ups for transport and storage of CO2 in Denmark have been outlined to compare their costs and to assess which set-ups or combinations of set-ups in Denmark is the most competitive. They include different transport and storage possibilities, meaning some set-ups will require ports and intermediate storage. It is Ramboll's assessment that no single storage site in Denmark is capable of handling 45 MtCO2/y alone. Meaning, that if a capacity of up to 45 MtCO2/y is desired, a combination of different set-ups must be used.

Table 4: Cost per ton for each set-up at 5 MtCO2/y (comprise transport and storage; CAPEX, accumulated OPEX and abandonment costs)

Set-up	#1	#2	#3	#4	#5	#6	#7	#8	#9
	Onshore; Shuttle tankers -> port -> storage site via pipeline	**Onshore**; shuttle tankers & pipeline (from CPH) -> port -> storage site via pipeline	**Nearshore;** Shuttle tankers -> port -> storage site via pipeline	**Nearshore;** Shuttle tankers & pipeline (CPH) -> port -> storage site via pipeline	**Offshore**, Shuttle tankers -> port -> storage site via pipeline	**Offshore**, Vessels -> injection site	**Offshore**, Shuttle tankers -> permanently moored FSU -> injection site	**Offshore**, Shuttle tankers & pipeline (from DE) -> port -> storage site via pipeline	**Offshore**, Shuttle tankers (SE, FI, PL & DK) -> port -> storage via pipeline; Pipeline from DE & NL -> storage
DKK/t	106	91	136	133	175	207	185	166	221

Note: Costs presented above are not levelised

In general, cost comparisons show that **onshore storage is the most cost-effective solution** (both when pipeline and sea transport is applied), **followed by nearshore storage** and with offshore storage as the most expensive solution. On the other hand, **pipelines provide scale advantage and is thus the most effective transport solution at large-scale**.

When other aspects than costs are considered, both onshore and offshore solutions and transportation options (pipeline and sea transportation) have advantages and disadvantages. In addition to being the least expensive option, **the onshore storage has the advantage of being located close to the large domestic CO2 emission sources** (Copenhagen area). However, **uncertainty whether the site can be used** (and thus need for seismic tests and drilling) and the general **risk of public opposition** can lead to a longer permitting process than in case of the offshore site.

Although the most expensive option, offshore storage offers several advantages, especially in the form of **general feasibility** and demonstrated tightness, and that it can be potentially **easier to obtain necessary permits** (especially for the onshore site). Furthermore, some of the **existing equipmen**t (platforms and support systems) **can be potentially reused**, meaning that the offshore solution can be **potentially even quicker implemented** than the onshore or nearshore solution.

Solutions with a pipeline from Germany would provide a more certain CO2 stream from abroad, making it potentially easier (and cheaper) to find investors. On the other hand, this type of solution is only meaningful when the full-scale operations are planned for construction from the beginning, while sea transportation enables small-scale start with gradual build-up. Note that a more gradual start is also possible in case of the onshore storage, where pipelines from sources and other connecting infrastructure can be added afterwards.

When assessing the competitiveness of Danish CO2 storage, the general criteria for competitiveness have been defined: a low-cost solution with low marginal cost and the ability to create a solution that allows flexibility. Based on that, it is Ramboll's assessment that **Denmark can offer a competitive solution highly that is both cost-effective, flexible and a convenient option for the target countries (especially Germany, Sweden, Finland and potentially Poland)**. The most cost-competitive solutions include set-ups where large CO2 amounts are contracted via pipeline and those that comprise or combine onshore and nearshore storage sites.

Institutional considerations suggest three main key take-aways:

- The necessity of **state involvement** in terms of funding (upfront capital expenditure), risk management and supporting the initiatives, since other actors do not have the capacity or economic incentive at present to drive the development for CCS on their own. Thus, there is most likely a need for state-aid and state involvement in Denmark as well, and the Danish Government will probably need to take a supportive role in the CCS initiative
- The need for a **body which acts on behalf of the state and administers and maintains the strategic overview** of the project progress and follow-up to ensure the project is progressing accordingly and the incentive structures are in place working efficiently to demonstrate market-based success

- The need for parties who possess **operational and technical experts** who can execute the business

The institutional considerations are one of the key prerequisites for the results of the business case set-ups. Mainly, it is important to note that the reference price presented in the profitability assessment entails state-aid. Thus, without state-aid, the revenue price and the business case results would not be feasible.

Profitability assessment of CO2 storage in Denmark

Based on the assessment of Denmark's competitive traits, three overarching business cases are considered to be the most competitive:

Table 5: Overview of the business cases

Case 1 & 2: Denmark to become primarily a small-to-medium sized domestic CO2 storage provider, while serving the international market in small-scale	**Case 3:** Denmark to become an established large-scale international CO2 storage provider while serving the domestic market simultaneously
In this case, Denmark is storing CO2 for 5 MtCO2/y (case 1) or 10 MtCO2/y (case 2) and will focus primarily on domestic CO2 volumes; There are **three different storage placement options for these cases**: • **1): Offshore small-scale storage with sea transportation only (no pipelines or ports) in the North Sea fields**, with vessels transporting CO2 directly from source points in Denmark to the offshore North Sea fields where it is injected • **2A): Onshore medium-scale storage in Havnsø**, with a pipeline from Copenhagen, and sea transport from other sources • **2B): Nearshore medium-scale storage in Hanstholm**, with a pipeline from Copenhagen and sea transport from other sources • **2C): Offshore medium-scale storage in the North Sea fields**, with a pipeline from Copenhagen to Esbjerg and shuttle tankers from various CO2 sources to Esbjerg (which is connected with the offshore site via a pipeline) **Note that small-scale cases could also be developed for onshore and nearshore storage, and these solutions could potentially have similar advantages and lower costs than the offshore solution in case 1. However, the scope of this report only comprises the offshore storage for the small-scale solution.*	In this case, Denmark is a large-scale CO2 storage provider for international markets. Denmark has a competitive advantage in terms of its location, as Denmark is strategically located in close proximity to Germany – the largest CO2 emitter in Europe – as well as Sweden, Finland, Poland and The Netherlands. Denmark can provide an attractive and cost-effective pipeline solution for German CO2 volumes, a pipeline spanning from Northern Germany to Esbjerg serving 20 MtCO2/y. In total, Denmark will store 40 MtCO2/y; 20 MtCO2/y from Germany; 15 MtCO2/y in total from Sweden, Finland and Poland, as well as 5 MtCO2/y domestically from Denmark. The large-scale international case is much more widespread in terms of the required CCS infrastructure than compared to case 1 & 2 and combines various storage and transport solutions to achieve desired scale and economies of scale.

Table 6: Cost per ton underlying each business case (comprise transport and storage; CAPEX, accumulated OPEX and abandonment costs)

	Case 1 (5 MtCO2/y)	**Case 2A** (10 MtCO2/y)	**Case 2B** (10 MtCO2/y)	**Case 2C** (10 MtCO2/y)	**Case 3** (10 MtCO2/y)
DKK/t	172	82	109	132	101
NPV	-2.0 BDKK	11.5 BDKK	5.5 BDKK	2.1 BDKK	26.6 BDKK
IRR	0.2%	12%	7%	5%	9%

Note: Costs per ton presented above are not levelised

Four out of five cases result in positive NPV values within a 30-year lifetime and range from a payback period between 8-25 years. However, it is **pivotal to note that the assessed business cases take a point of departure in the assumption that there will be a business case for CO2 storage providers, and the price will be a combination of, e.g., CO2 prices, CO2 taxes, grants etc**. However, the way in which the price is subsidised is not deemed necessary to assess the profitability and break-even of the business cases. Rather, it is important to forecast a price that is representative of a feasible market-based (i.e. competitive) scenario, and thus, we have developed a reference price for transport and storage, which is based on what it would cost for the export countries to export their CO2 to an offshore UK storage, which is deemed a representative, competitive and feasible alternative to Danish CO2 storage solutions. The reference price is based on an average of the various Danish offshore storage alternatives presented in the set-ups (Chapter 5.3). Further, utilising a reference price is seen as the most representative methodology, since forecasting the CO2 price and subsidy mechanisms includes high uncertainty and an array of the possible pathway (e.g., uncertainty around how income from CO2 costs, taxes and grants are allocated, since they are not solely allocated to CCS).

The business case scenario showing the highest positive **NPV; DKK ~26.6 billion, is case 3** (large-scale international CCS solution), which is mainly due to the high revenue volumes per year (40 MtCO2/y) and economies of scale from large-scale operations and from combining solutions e.g., pipelines utilised for different types of storages. Furthermore, this case includes all types of storages, meaning that CAPEX is lower than if only offshore storage was applied. Although case 3 has a significantly higher total cost than the domestic cases, the investment payback (**payback period is 11 years**) is expected sooner than for 1, 2B and 2C, again due to expected large CO2 volumes combined with economies of scale/ use of price-effective storage and transport solutions.

Although providing a clear advantage in form of flexibility, Case 1 (small-scale, domestically focused case with sea transportation only) **results in a negative NPV (DKK ~ (2.0) billion)** and the **longest payback period (25 years)**. The main reason is that this case has a considerably higher OPEX than the rest of the domestically focused cases and the highest cost per ton CO2 among all cases. However, it is important to note that the case is built on the assumption that only vessels will be used for the transportation of CO2 (which is the most expensive transportation solution) during the 30-year business case period. If the transportation is optimised during the ramp-up, by, e.g. adding a pipeline or permanently moored FSU, the business case could improve. At the same time, the revenue applied in the model is difficult to determine, and there is therefore associated uncertainty with regards to the business case results – i.e. business case would improve with higher revenue.

Case 2C (medium-scale, domestically focused case, with offshore storage) **posts an NPV of DKK ~2.1 billion** and a **payback period of 15 years**. While this is a positive NPV it is more expensive than 2A and 2C since offshore storage sites are more expensive than onshore and nearshore solutions.

Case 2A (medium-scale, domestically focused case, with onshore storage) **results in the second-highest NPV of DKK ~11.5 billion** and has the **shortest payback period (8 years)**. **Case 2B** (medium-scale, domestically focused case, with nearshore storage) has a **NPV of DKK ~5.5 billion and a payback period of 13 years**. This case has the highest CAPEX of all medium-size cases (i.e. 2A, 2B, 2C). However, OPEX is the second-lowest.

The results above are based on several prerequisites, including expected CO2 volumes, strong project management and identification of qualified, responsible parties, financial support (both nationally and in case 3 also internationally), that necessary permits are obtained without major delays, technological enhancement and ability to start the operations no later than 2030 (or at least in line with the volume uptake). Furthermore, some case-specific prerequisites apply, e.g. that the reservoirs (especially the less known onshore and nearshore storages) can be used for storage of CO2 and availability of the existing offshore pipeline infrastructure in time for the start of constructions works (and that it is possible to fully retrofit it to handle the large CO2 volumes) and that necessary international agreement, e.g., with German companies and state are secured upfront before the pipeline is constructed. For case 1 (small-scale and domestically focused case), one important prerequisite is that oil and gas companies possessing the concession rights are willing to switch from oil & gas activities to CO2 storage.

Furthermore, **pro's and con's have been compiled** for both case 1 & 2 (domestic solution) and case 3 (international solution).

It is essential to highlight that the domestic-oriented solutions are less complex and more affordable options (especially case 2A, which offers a highly price competitive option with the highest IRR and with the shortest payback period). However, when starting at a smaller scale, it can be in many cases more difficult to move towards large-scale and international market solutions than starting at large-scale from the beginning. On the other hand, the small-scale domestic case with vessel transportation (case 1) is the one providing the highest degree of flexibility, as it can be ramped up to the medium-scaled solution (or even large-scale, although choosing this way around can lead to lost opportunities), and modified into other solutions stepwise. Consequently, this case gives the possibility to explore the market before making the final decision on the strategic direction. However, this case has also the highest total cost per ton of CO2.

The internationally oriented solution (case 3) enables full utilisation of the market potential (and Denmark's strategic location, with close proximity to DE, SE, FI and PL) by offering a price competitive, convenient, and potentially binding solution. This solution can also play into the EU's plan to reach ambitious CO2 reduction targets and thus secure international financing and cost/risk-sharing. On the other hand, this solution is significantly more complex (although not unrealistic, as proven by the recent Baltic Pipe project), it would imply need for extensive state involvement and investments in widespread CCS infrastructure and also require EU to cooperate in continuing to support and pass policies that will aid the CCS market. Furthermore, this solution is the most meaningful if planned at large scale from the beginning - adding storages or infrastructure at a later time can impair the competitiveness of this system and also expected CO2 volumes.

Reflections on recommended next steps

Based on the assessment presented in this report, following next steps are recommended to move forward with planning of the CCS solution in Denmark:

- **A decision needs to be made with regards to whether import of foreign CO2** is desired
- **Realistic storage options should be mapped** based on internal preferences and ambitions. This should be followed by an assessment of whether there is economic optimisation potential in other combinations than presented in this report (e.g. large-to-medium-sized solutions)
- **Feasibility studies should be carried out** to gain a complete understanding of the potential and limitations of the considered solutions. This will also benefit and potentially speed up the process, as more detailed and reliable data can be presented and thus limit uncertainties and risks
- If the ambition is to become an established large-scale international CO2 storage provider, **initiation of strategic partnerships and collaborations (especially with German stakeholders) should be launched as soon as possible**. Similar alliances are currently existing within renewable energy – e.g. the North Sea Wind Power Hub, which is a consortium between Energinet, Gasunie and TenneT, jointly facilitating an accelerated deployment of large-scale offshore wind in the North Sea, and can be used for inspiration

4. CCS MARKET POTENTIAL

This chapter aims to provide a thorough understanding of the market potential for CCS in the Northern European countries covered in this analysis, with a particular emphasis on import opportunities, specified as the share of capturable CO2 intended for storage, that cannot be stored within the country's CO2 storage capacity.

The chapter, therefore, provides an overview of the link between CCS needs and the CO2 storage capacity within each of the Northern European countries and, based on this potential deficit, an assessment of the potential volumes that need to be exported to other countries.

4.1 KEY CONCLUSIONS ON THE CCS POTENTIAL IN NORTHERN EUROPE

This section provides a general overview of this chapter's key conclusions. For detailed elaborations, the report refers to the following sections covering each country concerning assessments of CCS potential in the country based on reviews of CO2 national targets and policies, estimations of volumes relevant for CCS, and estimations of CO2 storage potential.

Among the analysed countries, the highest emissions levels from large sources are found in Germany, Poland, UK, and the Netherlands, with MtCO2 emissions in 2017 at ~406, ~167, ~146, and ~95, respectively. However, **among the analysed countries, the report finds that the political support for CCS varies considerably**. The **countries with the most favourable national policies are Norway and the UK**, both of which have strong policies aimed at CCS, support schemes aimed at advancing the technology and projects to drive down costs, favourable regulatory CCS frameworks as well as targets or commitments towards its deployment, yet both countries highlight that deployment of CCS at scale is subject to costs coming down sufficiently. The Netherlands is ranked as the third-most CCS favourable country with respect to policy support, having strong policies aimed at CCS in place and targets for its deployment, yet considering CCS to be a transition solution. Countries ranked medium include Sweden, Germany, and Finland, which acknowledge CCS as necessary for reaching climate neutrality and have some supporting policies in place yet assessed not to be sufficient for large-scale CCS deployment. The **countries with least national focus on CCS include Poland and the Baltic countries** (i.e., Lithuania, Latvia, and Estonia) since none of the countries currently pursue CCS as a strategy to reach climate targets, indicated by the lack of supporting policies, funding schemes and regulation as well as lack of targets for its deployment. However, even these lowest ranking countries have acknowledged that CCS might potentially be relevant in the future, which may indicate growing political interest in the topic.

With respect to CCS potential, the report assesses that **UK, Germany, and Poland demonstrate the highest total volumes of capturable CO2 intended for storage ("CC potential")** among the analysed countries, with total estimated Mt CCS potential between 2022-2050 at 1,986, 871, and 591, respectively. In Germany, a large share of CCS potential is linked to fossil power plants (natural gas and biomass-fire plants), which is similar to Poland (coal and biomass CHP and natural gas), while in the UK the CCS potential is linked to both the power & heat sector (hydrogen) and hard-to-abate industries (mineral oil & gas refineries, minerals, iron and steel, chemicals and food). Although somewhat lower, **CCS potential is also assessed in Sweden, Finland, and the Netherlands** – in Sweden and Finland, the potential is mainly related to the pulp & paper industry, while in the Netherlands, the potential is a combination of both power plants (natural gas) and industry. The capturable potential in the Baltic countries is assessed to be insignificant due to low volumes.

The countries with their own CO2 storage capacity include the most significant emitters (Germany, Poland, UK, and the Netherlands) and Norway and Sweden, with estimated MtCO2 storage potential at 95,000, 78,000, 78,000, 4,000, 103,000 and 6,000, respectively. However, the **attitude towards domestic storage varies among the countries with storage potential** - while **UK and Norway have high ambitions for domestic storage (and even import of CO2 from abroad), Germany, Poland and Sweden are more reluctant towards domestic storage of CO2**. Low storage potential is estimated in Latvia and Lithuania, and for this reason, political attention to domestic storage is low, while unsuitable geological conditions in Finland and Estonia make domestic storage impossible.

The assessment of each country's possible needs to export CO2 for storage abroad, in order to reduce the deficit between CCS potential and domestic storage capacity finds that **the highest potential in relation to CO2 storage in Denmark is assessed with regards to Germany, Sweden and Finland**, as these countries have significant CCS potential and limited, or no storage capacity (or no intentions to use own storage). **Some potential, although more uncertain, could also be from the Netherlands,** since industry cluster projects, such as the CO2TransPorts, identify the risk that CO2 transport demand might exceed the storage capacity[3] and the Dutch Government acknowledges that it will be challenging for The Netherlands to achieve emissions reduction by scaling up renewables and thus, CCS could be a potential source to make up for this potential gap[3]. **Similarly, CO2 imported from Poland may also become relevant for storage in Denmark**, as it is highly uncertain whether (and when) Poland will utilise its own storage. The potential for Denmark is assessed below with regards to Norway and UK due to the high possibility that the countries will capture and store the CO2 domestically. In addition, no potential for Denmark is assessed in the Baltic countries, as emissions are insignificant and CCS potential is uncertain. The table below provides a quick overview of each individual country's CCS potential.

Table 7: Summary of CCS potential in selected countries

Country	FI	SE	NO	DE	UK	NL	PL	EE	LT	LV
CO2 emissions 2017 (MtCO2)	46.8	51.3	25.4	406.2	146.3	95.0	166.7	24.7	5.2	1.0
National CCS focus/support	◑	◑	●	◑	●	◕	◔	◔	◔	◔
CCS targets set	✗	✓	✓	✗	✓	✓	✗	✗	✗	✗
Total CCS potential (MtCO2) 2022-2050	279[4]	349	111	871	1,986	274	591	6	7	2
Average quantity of capturable CO2 intended for storage (MtCO2): - 2022-2040 - 2041-2050	7 16	14 19	4 6	35 49	50 119	12 15	19 34	0.2 0.4	0.4 0.3	0.1 0.1
Own storage capacity (Mt)	-	6,000	103,000	95,000	78,000	4,000	78,000	-	2,286	3,400
Own storage potential/support	N/R	◔	◕	◔	◕	◑	TBD	N/R	◔	◔
Potential for DK storage	**HIGH**	**HIGH**	**LOW**	**HIGH**	**LOW**	**MEDIUM**	**MEDIUM**	**LOW**	**LOW**	**LOW**

✓ The green tick mark indicates that the conditions for CCS are assessed to be favourable; ✗ The red cross indicates that the conditions for CCS are assessed to be unfavourable.
▬ The yellow bar indicates that it is uncertain whether the conditions for CCS are favourable or unfavourable. ○ Low value ● High Value

[3] European Commission, "Candidate PCI projects in cross-border carbon dioxide transport networks"
[4]IEA – The Netherlands 2020 Energy Policy Review

4.2 COUNTRY DEEP-DIVES

4.2.1 Finland

4.2.1.1 Summary of CCS potential in Finland

Finland's CO2 emissions from large sources in 2017 were ~47 MtCO2[5]. The largest emissions sources are pulp and paper (43%) and thermal power and heat (36%).

Finland aims to become carbon neutral in 2035, which is the most ambitious target of all countries. However, the country does not have any CCS specified targets and is relying heavily on natural carbon sinks from forests and soils to balance its emissions in 2035.

No national support systems for CCS development and deployment are in place in Finland.

CCS potential in Finland is estimated at 279 MtCO2 between 2022 and 2050 and on average 7 MtCO2/y between 2022 and 2040 and 16 MtCO2/y between 2041 and 2050 for both the power & heat sector and the industry sector. The potential has been assessed primarily with respect to BECCS, as Finland has the largest pulp and paper industry in Europe.

CO2 storage is not possible in Finland since the country does not have suitable geological formations.

The relevance for storage in Denmark is potentially high since potential bio-CCS is high, and Finland will not develop national storage sites.

Below is an overview of the CCS potential in Finland.

Table 8: Summary of CCS potential in Finland

SUMMARY OF CCS POTENTIAL		
Category	**Indicator**	**Comments**
CO2 emissions 2017 (MtCO2) Plants >100 ktCO2	46.8	CO2 emissions from the largest point sources, mainly generated by the pulp and paper industry using biomass, followed by the power and heat industry.
Co2 reduction targets	✓	• 2030: -39% from 2005 levels (non-EU ETS)[6] • 2035: Carbon neutral (all sectors) • 2050: -80-95% emissions mitigation from 1990 levels
National CCS focus/Support	◑	CCS has not been in the spotlight in Finnish policies and targets. However, in Finland's long-term GHG development strategy, CCS is presented in one of two potential pathways where Finland can achieve its long-term CO2e 2050 reduction goals[7].
CCS targets	✗	Finland has no CCS targets and has not mentioned CCS in its national energy and climate plan. Finland plans to phase out fossil fuels and rely on natural carbon sinks to achieve net-zero emissions.
Total CCS potential (MtCO2) 2022-2050	279	Finland's CCS potential is mostly comprised of potential from bio-CCS derived from the pulp and paper industry as well as power plants utilising biomass as fuel.
Own storage capacity (Mt)	- [8]	No suitable geological formations for CO2 storage are present in Finland
Own storage potential/support	○	Not relevant
Potential for DK storage	**High**	**Potentially high significance to DK due to high CCS potential, and the fact that Finland will not develop national storage sites.**

[5] EEA and E-PRTR

[6] Finland's Integrated National Energy and Climate Plan (NECP 2030) – CO2 reduction target for EU ETS sectors not available

[7] Finland will publish an updated Climate Act soon, which will enter into force in the spring of 2021, in which the target for 2050 (-80% emissions reduction) will be updated along with 2030 and 2040 targets that are in line with the path towards carbon neutrality in 2035

[8] Technical Research Centre of Finland "CO2 Capture, Storage and Reuse Potential in Finland"

4.2.1.2 CCS national targets and policies Finland

Finland is aiming to become carbon neutral in 2035. In the context of the Finnish Government Programme, "carbon neutrality" refers to a balance between Finland's regional GHG emissions and removals by sinks. Finland prioritises emissions reduction (mitigation) but notes in its government programme that it will heavily rely on natural carbon sinks (from forest and soil) as a supplemental measure. Current actions are not aligned with the target as these actions account for only 16 Mt of emissions reductions of the 35 Mt that will be necessary. To meet the gap (19 Mt), The Finnish Climate Change Panel estimates that carbon sinks will need to be at least 21.4 Mt.[9] The emissions reductions measure are carried out in a way that is fair from a social and regional perspective which involves all industries and sectors of society.

Finland does not have any CCS targets. However, in Finland's long-term greenhouse gas emission strategy, two pathways are described to reach carbon neutrality in 2035, one of which includes the usage of CCS (mainly from bio-CCS), where the total emissions reduction is estimated at 14 $MtCO_2e$ in 2050. The other pathway outlines extremely stringent emission reduction across all sectors (-87.5% reduction vs. -82% in the scenario with CCS in 2050), including industrial processes where it is deemed most difficult to achieve substantial reductions.

Finland has no national support system for CCS in place at the time. However, in 2011-2015 they ran a Carbon Capture and Storage research program allocating EUR 15 m for the CCS research.

Finland has implemented The Act on CCS, providing a general framework for CCS, with activities subject to the general environmental licensing system under the Environmental Protection Act. In addition, Finland has ratified the London Protocol that allows CO_2 export to other states for storage purposes. Additionally, Finland prohibits CO_2 storage due to the lack of suitable geological formations.

Table 9: CCS national targets and policies in Finland

CCS NATIONAL TARGETS AND POLICIES		
Category	**Indicator**	**Comments**
Country CCS policy maturity/potential	◐	The policy maturity considered low/medium since Finland follows the EU directive and has also implemented specific CCS legislation.
National CO_2 reduction targets	✓	• 2030: -39% from 2005 levels (non-EU ETS)[10] • 2035: Carbon neutral (all sectors) • 2050: -80-95% emissions mitigation from 1990 levels[11]
National CCS targets	✗	CCS targets have not been set.
CCS policies and legislations	–	Finland's CCS legal and regulatory framework is based upon the EU storage Directive and regulates activities through CCS-specific legislation, most notably The Act on CCS[12].
CCS funding	✗	No national support systems in place.
CCS storage-related policies	–	Finland has legislative limitations on geological storage in the Finnish territory because of the lack of suitable geological formations. However, storing volumes up to 100,000 tonnes for the purposes of research and development of technology may be permitted.[13]

[9] Finnish Government, "A fair transition towards a carbon neutral Finland"

[10] Finland's Integrated National Energy and Climate Plan (NECP 2030) – CO_2 reduction target for EU ETS sectors not available

[11] Finland will publish an updated Climate Act soon, which will enter into force in the spring of 2021, in which the target for 2050 (-80% emissions reduction) will be updated along with 2030 and 2040 targets that are in line with the path towards carbon neutrality in 2035.

[12] The Act on CCS provides the general framework for CCS, with activities subject to the general environmental licensing system under the Environmental Protection Act. CCS projects will also be subject to a mandatory Environmental Impact Assessment under national EIA legislation, whenever they are executed in facilities for which an EIA is mandatory, as well as whenever the overall amount of captured CO_2 under the project is 1.5 megatonnes or more.

[13] Legislation on carbon capture and storage

4.2.1.3 CCS potential (capturable CO2 intended for storage) in Finland

In 2017, Finland's large stationary sources emitted in round numbers ~47 MtCO2 in 2017, of which the power sector comprises ~17 MtCO2 and the industry ~29 MtCO2.

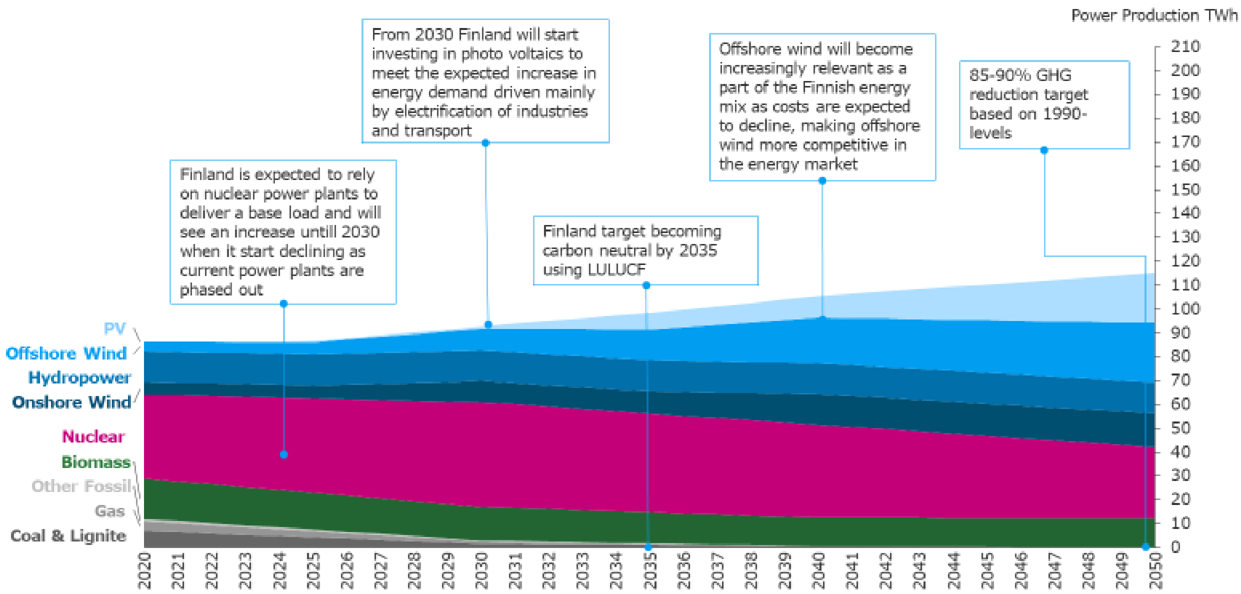
Finland is one of the leading pulp and paper producers in Europe and thus, has significant biogenic emissions from the pulp and paper industry - estimated at ~20 MtCO2 in 2017.

Additionally, the other industry sectors comprise mineral oil & gas refineries, cement production, iron and steel production as well as chemicals production, where some CCS potential is identified. CCS could pose a medium-term solution to remove fossil fuel CO2, according to the Ministry of Economic Affairs and Employment of Finland; especially if Finland is to achieve their ambitious carbon neutrality target in 2035, they will need to look into all mechanisms[14]. In the long-term, however, the goal is to remove all usage of fossil fuels in Finland, and this reduces the potential for CCS with regards to CO2 from fossil fuels.

Thermal power and heat generation (16.9 MtCO2 in 2017) sources are considered to have low to moderate potential since Finland is using and will use large shares of biomass at their CHP and district heating plants where bio-CCS could otherwise have potential.

The calculated capturable quantity of CO2 intended for storage (CCS potential) is estimated at an average 7 MtCO2/y between 2022 and 2040 and 16 MtCO2/y between 2041 and 2050 for both the power & heat sector and the industry sector.

Figure 1: Finland's potential energy mix towards 2050



Source: Ramboll Analysis; Ministry of Economic Affairs and Employment of Finland, "Finland's long-term low greenhouse gas emissions development strategy"

[14] Interview with Ministry of Economic Affairs and Employment of Finland

Table 10: CCS potential in Finland

Sector	CO2 emissions 2017, MtCO2	Capturable quantity of CO2, MtCO2 (avg. MtCO2/y[15])		Comment
		2022-2040	2041-2050	
Power & Heat	**17.1**	**32** **(2)**	**57** **(6)**	• The overall significance of CCS within the Finnish power & heat sector is considered low to moderate due to Finland's large usage of biomass within this sector, which could be relevant for BECCS. Finland is to date one of the leading countries in forest-based biomass to energy, and this is expected to remain at stable levels, while other forms of energy such as renewable and nuclear are making up for the power and heat growth going forward[16]. Finland has some of the largest power plants situated by the shore in Helsinki, which incentivises the usage of BECCS since the country does not have to transport these amounts by land • The potential for BECCS is estimated to begin from 2025 as Finland is assumed to deploy carbon reduction measures sooner due to its carbon neutrality target already in 2035. The capture share for BECCS is assumed to increase from 5% in 2025 and increases to 80% in 2050 • The capturable volume of CO2 intended for storage within the segment is estimated at ~5.7 MtCO2/y in 2050
Industry	**29.4**	**87** **(5)**	**103** **(10)**	• Finland has quite small amounts of emissions coming from the fossil fuel-driven industry, which is relevant for CCS, including mineral oil & gas refineries (3.1 MtCO2/y), cement production (1.3 MtCO2/y), iron and steel production (1.5 MtCO2/y) as well as chemicals production (0.7 MtCO2/y) • The significance of CCS for the fossil driven industrial sector is low since Finland is prioritising natural carbon sinks as opposed to carbon removal technologies. However, if Finland is to reach their ambitious carbon neutrality target in 2035, it will need to consider all options to reduce its emissions • Ramboll has assumed that CCS could be used in the industry already starting from 2025 to achieve the climate goals and continue from a 5% capture share up to 30% towards 2050. However, according to the Ministry of Economic Affairs and Employment, CCS for fossil fuels will be a medium-term solution since coal, and natural gas will be phased out in the long term, and according to scenario studies, 82-87.5% (compared to 1990 levels) of emissions are mitigated by 2050[17].**Error! Bookmark not defined.** Thus, Ramboll has estimated a decrease of CO2 within the industry to follow this trajectory • The total capturable volume intended for storage is estimated at up to ~1 MtCO2/y in the early 2030s and decreases to 0.5 MtCO2/y in 2050, as fossil fuels are phased out • In addition to the industries above, Finland has a significant pulp and paper industry, and thus, bio-CCS could be relevant. Pulp & paper plants are often located close to coastlines and rivers (as their processes require significant amounts of water), making it potentially easily accessible to collect emissions. • Additionally, bio-CCS is not part of Finland's current climate strategy, but they might deploy it to meet their climate goals. As with the other industries above, the deployment is assumed from 2025 with a 5% capture rate until however in contrast to the above, the rate increases to 60% in 2050 • The total capturable volumes intended for bio-CCS (pulp and paper industry) is estimated at up to 9.7 Mt/y (from ~2035)
Other	**2.9**	**-**	**-**	• No other significant potential areas have been assessed

[15] Average CO2 capturable amount is calculated for the time period 2025-2040 as well as 2041-2050

[16] Ministry of Economic Affairs and Employment of Finland, "Finland's long-term low greenhouse gas emission development strategy", 2020

[17] Ministry of Economic Affairs and Employment of Finland, "Finland's long-term low greenhouse gas emission development strategy", 2020

4.2.1.4 CO2 storage potential in Finland

Finland does not have any geological structures suitable for carbon storage[18].

Moreover, the country does not currently have any carbon capture projects[19]but has allowed carbon export, as described in section 4.2.1.2. The Finnish attitude to CCS technology is favourable, but legislative barriers are currently preventing implementation[20].

Finland will not be able to domestically store captured carbon from any upcoming CCS activity and will have to utilise CO2 storage capacity in other countries.

4.2.2 Sweden

4.2.2.1 Summary of CCS potential in Sweden

Sweden's CO2 emissions from large sources in 2017 were ~51 MtCO2. Most emissions relate to the pulp and paper industry using biomass (22.8 MtCO2).

Sweden is committed to achieving climate neutrality by 2045, and CCS is acknowledged as a means of achieving negative emissions, mainly through the deployment of BECCS. CCS policy measures such as investment support are in place, though currently not identified to be sufficient for the realisation of full-scale projects. CCS targets have been set for 2030 (3.7 MtCO2e total, of which 1.8 MtCO2 from BECCS) and 2045 (10.7 MtCO2e total, of which 3-10 MtCO2 from bio-CCS). To achieve Sweden's climate targets, ~9% of required emissions reductions by 2030 and 15% by 2045 can be achieved through other complementary means such as CCS.

Support systems for CCS are in place through, e.g., the Swedish Energy Agency, allocation of SEK 100 million to CCS and BECCS pilot projects, and initiatives to support R&D projects within bio-CCS with SEK 50 million annually from 2020-2027.

CCS potential in Sweden is estimated at 349 MtCO2 between 2022 and 2050 and 14 MtCO2/y between 2022 and 2040, and 19 MtCO2/y between 2041 and 2050. The majority of these emissions relate to the pulp and paper industry.

Storage potential in Sweden is estimated at 6,000 Mt in aquifers. Although offshore CO2 storage is permitted, Sweden is expected to rely on the transport of CO2 as the Swedish official report on a strategy for negative greenhouse gas emissions concluded that rather than prioritising establishing a storage site, Sweden should depend on sea transport to storage outside Sweden.

The relevance for storage in Denmark is deemed high, as Sweden has national plans to develop CCS technology but not for the development of national storage sites.

Below is an overview of the CCS potential in Sweden.

Table 11: Summary of CCS potential in Sweden

SUMMARY OF CCS POTENTIAL		
Category	**Indicator**	**Comments**
CO2 emissions 2017 (MtCO2) Plants >100 ktCO2	51.3	CO2 emissions from largest point sources; mainly by the pulp and paper industry using biomass, followed by the heat and power generation, and iron and steel industry
CO2 reduction targets	✓	• 2030: -20% from 2005 levels (EU ETS) and -63%[21] from 1990 levels (non-EU ETS)[22] • 2040: -75% from 1990 levels (national target)[23] • 2045: Net zero emissions

[18] Technical Research Centre of Finland, "CO2 capture, storage and reuse potential in Finland"

[19] The Global CCS Institute, "Global Status of CCS 2020"

[20] Interview with Ministry of Economic Affair and Employment of Finland

[21] Equivalent to -59% reduction from 2005 levels

[22] Sweden's Integrated National Energy and Climate Plan (NECP 2030)

[23] Regeringens Proposition 2019/20:65: "En samlad politik för klimatet – klimatpolitisk handlingsplan"

National CCS focus/Support	◑	Sweden recognises the important role that CCS will have in reaching CO2 reduction targets, yet current policy measures may not be sufficient for realisation of full-scale CCS projects.
CCS targets	✓	Sweden has set CCS targets for 2030 (3.7 MtCO2e total, whereof 1.8 MtCO2 from bio-CCS) and 2045 (10.7 MtCO2e total, whereof 3-10 MtCO2 from bio-CCS). ~9% of the required reductions in CO2 emissions by 2030 and 15% by 2045[24] can be achieved through other complementary means such as CCS.
Total CCS Potential (MtCO2) 2022-2050	349	The majority of these emissions is related to the pulp and paper industry.
Own storage capacity (Mt)	6,000[25]	6,000 Mt of storage in aquifers
Own storage potential/support	◔	Offshore CO2 storage is permitted. However, Sweden is expected to rely on the export of CO2 as uncertainty regarding national storage capacity was deemed too high while reliable storage sites in the North Sea were available
Potential for DK storage	**High**	**High significance to DK as Sweden has national plans to develop CCS technology but not to develop storage sites.**

4.2.2.2 CCS national targets and policies Sweden

Sweden is aiming to become carbon neutral in 2045, expecting 85% of reductions to be delivered through emissions reduction activities while the remaining 15 percentage points may be covered by supplementary measures such as CCS (incl. BECCS)[26]. Sweden has set CCS targets for 2030 (3.7 MtCO2e total, whereof 1.8 MtCO2 from bio-CCS) and 2045 (10.7 MtCO2e total, whereof 3-10 MtCO2 from bio-CCS). To reach Sweden's -63% CO2 reduction target by 2030, ~9% of the required reductions in CO2 emissions may be achieved through other means such as CCS[27].

Policy measures such as investment support are in place, though currently not identified to be sufficient for the realisation of full-scale CCS projects. The Swedish government has recently decided to ratify the amendment to the London protocol. This was mentioned as a necessary action in the national energy and climate plan to allow for the development of CCS in the country[28].

The Swedish state has in place some financing mechanisms for CCS-related projects through the Swedish Energy Agency. In 2019, the Swedish government allocated SEK 100 million to pilot projects aimed at accelerating the deployment of CCS and BECCS. Through the Industriklivet initiative, support is given to R&D projects which contribute to negative emissions, for example, bio-CCS. The support is planned to be at SEK 100 million annually until 2020, thereafter SEK 50 million annually until 2027.[29]

Sweden regulatory framework for CCS is primarily stand-alone and based upon the regulatory permissions model found in the Swedish Environmental Code. In addition, further permissions are required under the Continental Shelf Act and the Certain Pipelines Act. While the Swedish regulatory framework addresses many key issues, some critical elements have not been fully addressed, including the explicit definition of CO2 and CO2-specific transportation provisions. Sweden has placed restrictions on where CO2 may be stored and the activities that may take place within the Swedish Economic Zone and offshore sites[30].

Sweden's official report on a strategy for negative GHG emissions considered storage from Swedish CCS. While the report specified that it is likely that there is domestic storage in Sweden, knowledge about their capacities was deemed to be poor. The strategy concluded that Sweden should not prioritise establishing a storage site but rather depend on sea transport to storage outside Sweden, for example, Norway or another North Sea country.

[24] Klimat politiska rådet "2020: Report of the Swedish Climate Policy Council"
[25] Uppsala University "A Probabilistic Assessment of the Effective CO2 Storage Capacity within the Swedish sector of the Baltic Basin
[26] 2020 Report of the Swedish Climate Policy Council
[27] Klimat politiska rådet "2020: Report of the Swedish Climate Policy Council"
[28] Regeringens Proposition 2019/20:65: "En samlad politik för klimatet – klimatpolitisk handlingsplan"
[29] THEMA Consulting Group "The role of Carbon Capture and Storage in a Carbon Neutral Europe"
[30] Global CCS Institute CO2RE database

Table 12: CCS national targets and policies in Sweden

CCS NATIONAL TARGETS AND POLICIES		
Category	**Indicator**	**Comments**
Country CCS policy maturity/potential	◐	CCS recognised as a potentially important means of reaching climate targets, and CCS target has been specified, yet lack of sufficient policy measures and restrictions in the legal framework creates a medium maturity level.
National CO2 reduction targets	✓	• 2030: -20% from 2005 levels (EU ETS) and -63%[31] from 1990 levels (non-EU ETS)[32] • 2040: -75% from 1990 levels (national target)[33] • 2045: Net zero emissions
National CCS targets	✓	Sweden has set CCS targets for 2030 (3.7 MtCO2e total, whereof 1.8 MtCO2 from bio-CCS) and 2045 (10.7 MtCO2e total, whereof 3-10 MtCO2 from bio-CCS). ~9% of the required reductions in CO2 emissions by 2030 and 15% by 2045[34] can be achieved through other complementary means such as CCS.
CCS policies and legislations	–	Policy measures such as investment support are in place, though currently not identified to be sufficient for the realisation of full-scale projects. Sweden's regulatory framework for CCS is primarily stand-alone and based upon the regulatory permissions model found in the Swedish Environmental Code.
CCS funding	–	The Swedish state has in place some financing mechanisms for CCS-related projects through the Swedish Energy Agency.
CCS storage-related policies	–	Offshore CO2 storage is permitted. The Swedish official report on a strategy for negative greenhouse gas emissions specified that there is likely domestic storage in Sweden. Yet, knowledge about their capacities was deemed to be poor. The strategy concluded that Sweden should not prioritize establishing a storage site but rather depend on sea transport to storage outside Sweden, for example, Norway or another North Sea country.[35]

4.2.2.3 CCS potential (capturable CO2 intended for storage) in Sweden

Sweden's emissions from large sources were 51 MtCO2 in 2017, of which 16.5 MtCO2 were from the power & heat industry, 11.8 MtCO2 from the energy-intensive industries and 22.8 MtCO2 from pulp and paper production.

The calculated capturable quantity of CO2 from large sources is estimated at on average 14 MtCO2/y between 2022 and 2040 and 19 MtCO2/y between 2041 and 2050. The majority of these emissions is related to the pulp and paper industry.

[31] Equivalent to -59% reduction from 2005 levels

[32] Sweden's Integrated National Energy and Climate Plan (NECP 2030)

[33] Regeringens Proposition 2019/20:65: "En samlad politik för klimatet – klimatpolitisk handlingsplan"

[34] Klimat politiska rådet "2020: Report of the Swedish Climate Policy Council"

[35] THEMA Consulting Group "The role of Carbon Capture and Storage in a Carbon Neutral Europe"

Table 13: CCS potential (intended for storage) in Sweden

Sector	CO2 emissions 2017, MtCO2	Capturable quantity of CO2, MtCO2 (avg. MtCO2/y[36])		Comment
		2022-2040	2041-2050	
Power & Heat	**16.5**	**43** (4)	**48** (5)	• The overall significance of CCS within the Swedish power & heat sector is low due to renewable power generation. However, BECCS has been emphasised as an important additional measure to achieve negative emissions in 2045 (although no specific CCS targets have been made for CCS) • Forest is the largest source of bioenergy in Sweden (63% of land cover). Bioenergy is primarily used for heating – both in private homes and in district heating – as well as for electricity production and for industrial processes[37] • In order to meet the ambitious carbon neutrality targets towards 2045, the first projects are expected to be introduced before 2030 • The capturable volume of CO2 intended for storage within the segment is estimated at up to ~5 MtCO2/y, and is executively related to emissions from biomass-fired energy and heat plants (incl. waste-to-energy plants)
Industry	**11.8**	**116** (11)	**143** (14)	• Process emission within the energy-intensive industry were 11.8 MtCO2 in 2017, mainly related to the production of iron and steel (4.1 MtCO2), cement (2.8 MtCO2) and refining (2.7 MtCO2) • For the remaining industries, green hydrogen and electricity are expected to be preferred • The total capturable volume intended for storage is estimated at up to ~3 MtCO2/y • In addition to the industries above, Sweden is one of the major pulp and paper producers in Europe. Associated emissions were estimated at ~22.8 MtCO2 in 2017. Pulp & paper plants are often located close to coastlines and rivers (as their processes require significant amounts of water), making it potentially easily accessible to collect emissions. • The total capturable volumes intended for CCS are estimated at up to 11 MtCO2/y (in 2014; ramping gradually up from 2028 where the technology is assumed to be introduced)

4.2.2.4 CO2 storage potential in Sweden

Sweden has 6,000 Mt of total carbon storage situated in aquifers[38]. While the storage capacity is adequate to cover all upcoming CCS activity, no investments in developing the storage sites have been made, as described in section 4.2.2.2.

The Swedish attitude towards CCS is generally positive[39], as incentive schemes are in place to develop CCS technology. Moreover, several studies are currently underway to hook up local fossil fuel power generation and industry in the Gothenburg area to CO2 export infrastructure, enabling storage of Swedish carbon in the North Sea area[40].

As a result, Sweden seemingly has no intention of developing domestic carbon storage sites and prioritises developing carbon export infrastructure while looking for international opportunities to store the captured carbon.

[36] Average CO2 capturable amount is calculated for the time period 2030-2040

[37] Sweden.se/ Swedish Institute

[38] Uppsala University, "A Probabilistic assessment of the effective CO2 storage capacity within the Swedish Sector of the Baltic Basin"

[39] IOGP, "The potential for CCS and CCU in Europe"

[40] DEA/Ramboll, "Catalogue of Geological Storage of CO2 in Denmark"

4.2.3 Norway

4.2.3.1 Summary of CCS potential in Norway

Norway's CO2 emissions from large sources in 2017 were ~25 MtCO2. Most emissions relate to the energy-intensive energy sector (11.2 MtCO2) since power generation is mainly from hydroelectric plants.

Norway has created favourable conditions for the development and use of CCS through solid policy and regulatory support and dedicated action plans for CCS. Yet, no specific targets for CCS deployment have been set. However, the processing industry has created a roadmap for achieving climate targets towards 2050, including 33% from CCS and 20% from BECCS.

Extensive support systems for CCS are in place through various organisations and research centres, among others the Norwegian CCS Research Centre (NCCS) in 2016, with 30 research and industry partners and a budget of NOK 570 million over eight years. Key drivers for Norway's successful CCS development projects have been the supporting policy framework and high CO2 prices.

Norway's CCS potential within the processing industry is high; 111 MtCO2 in total between 2022 and 2050, and on average 4 MtCO2/y between 2022 and 2040 and 6 MtCO2/y between 2041 and 2050. Energy majors are expected to see CCS as a way of protecting their existing extraction and refining business. At the same time, fossil-reliant industries such as steel could choose to use CCS rather than invest in options like hydrogen.

Storage potential in Norway is estimated at 103,000 Mt, of which 76,000 Mt of storage in aquifers and 27,000 Mt of storage in depleted oil & gas fields.

The relevance for storage in Denmark is deemed low, as Norway has national plans to develop CCS technology and develop storage sites.

Below is an overview of the CCS potential in Norway.

Table 14: Summary of CCS potential in Norway

SUMMARY OF CCS POTENTIAL		
Category	**Indicator**	**Comments**
CO2 emissions 2017 (MtCO2) Plants >100 ktCO2	25.4[41]	CO2 emissions from the largest point sources; mainly from the power and heat generation industry, followed by the iron and steel, non-ferrous metals and mineral oil and gas industry
CO2 reduction targets	✓	• 2030: -50% from 1990 levels[42] (economy wide) and -30% from 2005 levels (non-EU ETS)[43] • 2050: -90-95% from 1990 levels (economy wide)
National CCS focus/Support	●	Strong policy and regulatory support, as well as dedicated actions plans for CCS, create favourable conditions for the development and use of CCS in Norway.
CCS targets	✓	Norway has not set specific targets for CCS deployment, with the justification by the Norwegian Ministry of Climate and Environment that it is not possible to quantify the emission reductions that might be realized through Norway's CCS policies as it will, for most parts, take place in the industry covered by the EU ETS[44]. However, the Norwegian processing industry has created a roadmap for 2050 for achieving its long-term national climate targets: deploy CCS to reduce as much as 33% of planned emission reductions and ~20% from CCS combined with combustion of biogenic matter. Further, long-standing policy and research commitments suggest that CCS will become an important means to achieving Norway's long-term target of

[41] EU Emissions Trading Scheme data – Does not include biogenic emissions

[42] Norway's Fourth Biennial Report. In its National Determined Contribution (NDC) under the Paris Agreement and committed to reduce emissions by at least 50 per cent and towards 55 per cent by 2030 compared to 1990.

[43] Norwegian Ministry of Petroleum and Energy "Longship – Carbon Capture and Storage"

[44] Norwegian Ministry of Climate and Environment "Norway's Fourth Biennial Report"

		reducing CO2 emissions by 90-95% by 2050, despite the current lack of specified targets for CCS.
Total CCS Potential (MtCO2) 2022-2050	111	Primarily related to refining and other fossil-reliant industries (e.g. iron & stell)
Own storage capacity (Mt)	103,000[45]	76,000 Mt of storage in aquifers; 27,000 Mt of storage in depleted oil & gas fields;
Own storage potential/support		Large offshore storage sites are being developed with large investments from the government
Potential for DK storage	**Low**	**Low significance to DK as NO has national plans to develop CCS technology but also to develop storage sites (and has sufficient storage capacity)**

4.2.3.2 CCS national targets and policies in Norway

Norway aims to become a low-emission society by 2050, targeting reducing greenhouse gas emissions between 90-95%[46]. Norway has identified CCS as important for achieving these targets. Overall, the policy maturity is considered high as CCS strategies, policies, supportive legislative frameworks, and support systems have created favourable conditions for CCS in Norway.

The Norwegian Government has developed a CCS strategy, which includes research, development and demonstration, an ambition to realize a full-chain demonstration facility, transportation, storage and alternative use of CO2 and international work for the implementation of CCS as a mitigation measure[47]. Important parts and tasks are given to the Research Council of Norway and Gassnova (a state-backed body whose mission is to realise CCS solutions)[48]. In 2020, the Norwegian government proposed to launch a CCS project called "Longship", which will demonstrate a full, but flexible value chain with carbon capture from cement production and potentially from waste management and shipping, and CO2 storage beneath the seabed.

Norway has not set specific targets for CCS deployment, with the justification by the Norwegian Ministry of Climate and Environment that it is not possible to quantify the emission reductions that might be realized through Norway's CCS policies as it will, for most parts, take place in the industry covered by the EU ETS[49]. However, the Norwegian processing industry has created a roadmap for 2050 for achieving its long-term national climate targets, according to which it needs to deploy CCS to reduce as much as 33% of planned emission reductions and ~20% from CCS combined with the combustion of biogenic matter[50]. Further, long-standing policy and research commitments suggest that CCS will become an important means to achieving Norway's long-term target of reducing CO2 emissions by 90-95% by 2050, despite the current lack of specified targets for CCS.

Norway has demonstrated a commitment to the deployment of CCS and to drive down technology costs through extensive support systems targeted at CCS research and projects. Norway established the Norwegian CCS Research Centre (NCCS) in 2016, with 30 research and industry partners and a budget of NOK 570 million over eight years[51]. Further, Norway's Technology Centre Mongstad (TCM) has established itself as a leading international competence centre for the demonstration of capture technology[52]. The Norwegian Government and the current industry owners of TCM have entered into a new operating agreement from the end of August 2020 until the end of 2023[53]. In addition, the national research programme CLIMIT is an essential source of funding for research and demonstration of IS technology. In addition, the government has established a strategic committee for clean energy research called ENERGI21, under which CCS is one of six priority focus areas. Other key funding programmes include SkatteFUNN, which

[45] Nordic CCS Competence Centre "CO2 Storage Potential in the Nordic Region"
[46] Norwegian Ministry of Climate and Environment "Norway's National Plan"
[47] Norwegian Ministry of Climate and Environment "Norway's Fourth Biennial Report"
[48] Norwegian Ministry of Petroleum and Energy "Longship – Carbon Capture and Storage"
[49] Norwegian Ministry of Climate and Environment "Norway's Fourth Biennial Report"
[50] Norwegian Ministry of Petroleum and Energy "Longship – Carbon Capture and Storage"
[51] Norwegian Ministry of Petroleum and Energy "Longship – Carbon Capture and Storage"
[52] Norwegian Ministry of Petroleum and Energy "Longship – Carbon Capture and Storage"
[53] Norwegian Ministry of Petroleum and Energy "Longship – Carbon Capture and Storage"

provides tax incentives for CCS related research, as well as Accelerating CCS Technology (ACT), which is a European initiative managed by Norway to establish CCS.

The supporting policy framework and high CO2 prices have been crucial drivers for the development of Norway's successful CCS projects. The Longship project proposed by the Norwegian government requires funding of USD 2.7 billion, and will also comprise funding for the transport and storage project Northern Lights, a joint project between Equinor, Shell and Total[54]. The CCS projects from natural gas on the Sleipner, Gudrun and Snøhvit petroleum fields are the only CCS projects currently in operation in Europe and the only projects in the offshore industry.

Norway does not have CCS-specific legislation; however, amendments to existing regulation have created a comprehensive regulatory framework for the transport and storage of CO2 in Norway. National pollution, environmental and petroleum legislation is sufficient to cover CCS, and amendments have been made to regulations concerning the storage of CO2 in offshore sub-sea reservoirs on the Norwegian continental shelf. Norway has implemented the EU CCS Directive, which has provided a basis for amendments to existing legislation. In addition, Norway has ratified the London Protocol that allows CO2 export to other states for storage purposes. Yet, the Protocol has not entered into force as too few countries have ratified it.

Table 15: CCS national targets and policies in Norway

CCS NATIONAL TARGETS AND POLICIES IN NORWAY		
Category	**Indicator**	**Comments**
Country CCS policy maturity/potential	●	The policy maturity is considered high due to CCS strategies, policy, legislative frameworks and support systems, creating favourable conditions for CCS.
National CO2 reduction targets	✓	• 2030: -50% from 1990 levels[55] (economy wide) and -30% from 2005 levels (non-EU ETS)[56] • 2050: -90-95% from 1990 levels (economy wide)
National CCS targets	✗	CCS targets have not been set.
CCS policies and legislations	✓	The Norwegian government has developed a national CCS strategy, created state-sponsored CCS authorities and recently proposed a project to demonstrate a full but flexible value chain with carbon capture from cement production and potentially from waste management and shipping, and CO2 storage beneath the seabed. Norway does not have CCS-specific legislation; however, amendments to existing regulation have created a comprehensive regulatory framework for the transport and storage of CO2 in Norway.
CCS funding	✓	The government supports CCS through various supporting schemes and R&D funding. National CCS centres, CCS funding programmes have been influential in the development of Norway's successful CCS projects.
CCS storage-related policies	✓	Offshore storage is permitted.

[54] Norwegian Ministry of Petroleum and Energy "Longship – Carbon Capture and Storage"

[55] Norway's Fourth Biennial Report. In its National Determined Contribution (NDC) under the Paris Agreement and committed to reduce emissions by at least 50 per cent and towards 55 per cent by 2030 compared to 1990.

[56] Norwegian Ministry of Petroleum and Energy "Longship – Carbon Capture and Storage"

4.2.3.3 CCS potential (capturable CO2 intended for storage) in Norway

Norway's emissions from large sources were 25 MtCO2 in 2017. The majority of emissions is related to energy-intensive sectors since power generation in Norway is almost entirely from hydroelectric power plants.

Norwegian government accords great importance to CCS. Energy majors are therefore expected to see CCS as a way of protecting their existing extraction and refining business. Furthermore, fossil-reliant industries such as steel could use CCS rather than invest in options like hydrogen. CCS will also be needed to deploy blue hydrogen.

The calculated capturable quantity of CO2 is estimated at an average of 4 MtCO2/y between 2022 and 2040 and 6 MtCO2/y between 2041 and 2050.

Table 16: CCS potential (intended for storage) in Norway

Sector	CO2 emissions 2017, MtCO2	Capturable quantity of CO2, MtCO2 (avg. MtCO2/y[57])		Comment
		2022-2040	2041-2050	
Industry	**11.2**	**33** (3)	**49** (5)	• Process emission within energy-intensive industry were 11.2 MtCO2 in 2017, mainly related to refining (2.6 MtCO2), iron and steel production (2.5 MtCO2) and non- ferrous metals (2.7 MtCO2) • The significance of CCS within the industrial sector is assessed to be relatively low and is mainly relevant for cement and refining (where there are currently no other ways to reduce the process emissions significantly). It is often only one of the available options (and less preferred) within other industrial subsectors, including iron and steel and chemicals. Moreover, in many countries, the industrial sector prefers CCU instead of CCS. However, in Norway, the government accords great importance to CCS. Energy majors are therefore expected to see CCS as a way of protecting their existing extraction and refining business. Furthermore, fossil-reliant industries such as steel could use CCS rather than invest in options like hydrogen. CCS will also be needed to deploy blue hydrogen. • The total capturable volume intended for storage is estimated at up to ~5 MtCO2/y
Fuel combustion	**14.2**	**15** (1)	**14** (1)	• Fuel combustion is presumably related to oil & gas activities • The significance of CCS is assessed to be high in this context, as energy majors are expected to prioritise CCS, due to governmental focus on this decarbonisation measure. The total capturable volume intended for storage is estimated at up to ~2 MtCO2/y (peak between 2033 and 2040)

[57] Average CO2 capturable amount is calculated for the time period 2030-2040

4.2.3.4 CO2 storage potential in Norway

Norway has 103,000 Mt of carbon storage in suitable geological structures, of which the majority (76,000 Mt) is situated in aquifers and 27,000 Mt in located in oil and gas field units[58]. All known storage units are located offshore in the North Sea and the Norwegian Sea on the Norwegian Continental Shelf near current oil and gas fields[59].

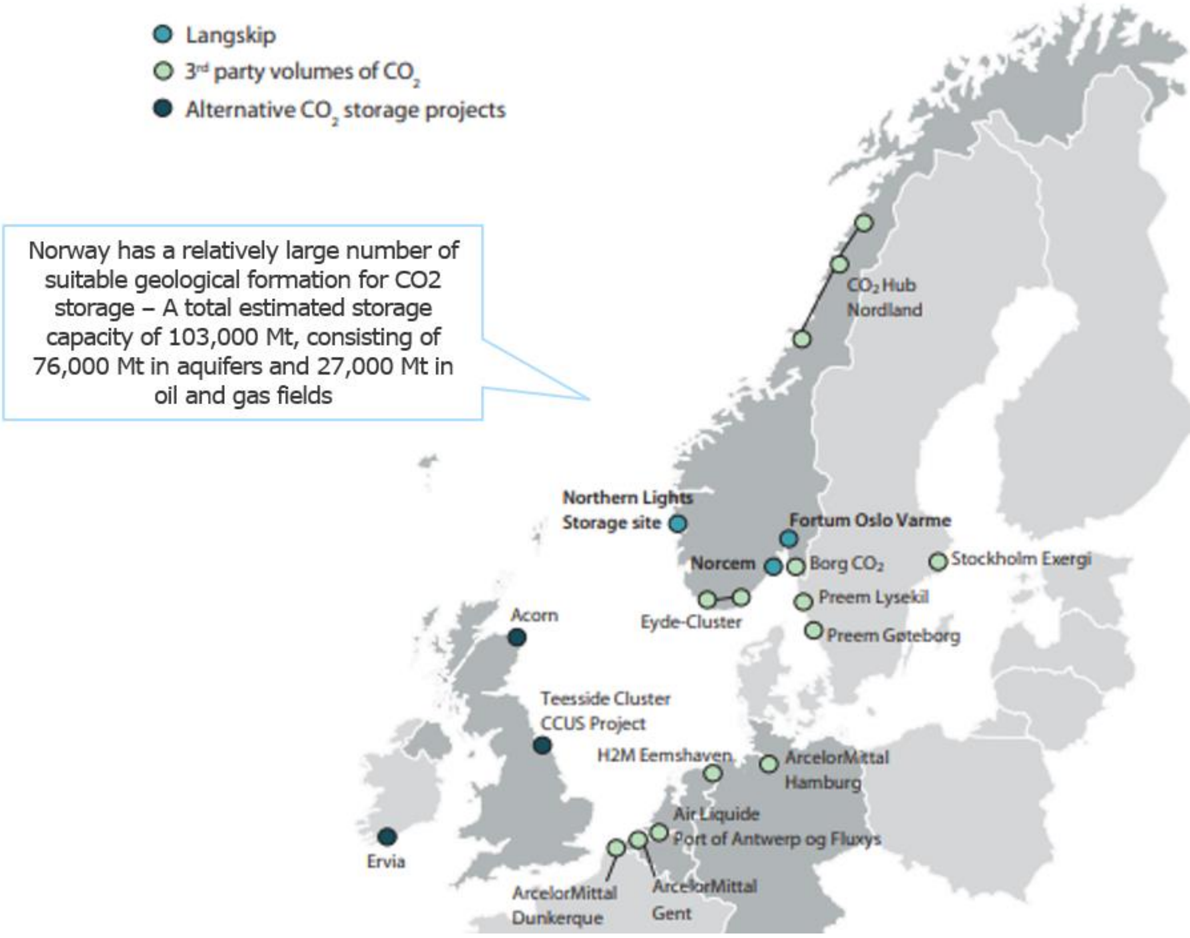
Carbon storage in oil and gas fields can be cheaper to develop than aquifer storage units as some of the offshore infrastructure is already in place[60].

Norwegian attitude and legislation are favourable towards CCS technology and offshore carbon storage, as described in section 4.2.3.2.

As a result, the carbon storage capacity of Norway is considered sufficient to cover all upcoming CSS activity and will be sufficient to store CO2 imports from other countries[61].

The figure below provides an overview of the CCS projects in Norway.

Figure 2: Overview of CCS facilities in Norway



Source: Norwegian Ministry of Petroleum and Energy, "Longship – Carbon capture and storage", Ramboll analysis

[58] Nordic CCS Competence Centre, "CO2 Storage potential in the Nordic region"
[59] EU GeoCapacity, "Assessing European capacity for Geological Storage of Carbon Dioxide"
[60] IOGP, "The potential for CCS and CCU in Europe"
[61] Ramboll Expert

4.2.4 Germany

4.2.4.1 Summary of CCS potential in Germany

Germany's emissions from large sources in 2017 were ~406 MtCO2. The energy sector is one of the largest single sources of CO2 emissions in Europe.

Germany aims to become climate neutral in 2050, and as Europe's largest emitter, CCS will most likely become a significant means of reaching this climate target. The role of CCS for reaching carbon neutrality has been noted in Germany's Climate Action programme as unavoidable and by former Chancellor Angela Merkel at the Petersburger Klimadialog to be necessary. However, currently, Germany has not set any CCS targets.

To support the deployment of CCS, Germany is preparing a subsidy programme aimed at the country's raw material industry for developing CCU and CCS technologies, with a budget at EUR 105 million for 2021 and, after that, an additional EUR 120 million per year until 2025.

CCS potential in Germany is estimated at 871 MtCO2 between 2022 and 2050 and on average 35 MtCO2/y between 2022 and 2040 and 49 MtCO2/y between 2041 and 2050, from close to 200 different large power and industrial processing facilities. The largest share of capturable CO2 is expected to be derived from the power & heat sector (natural gas-fired power plants and biomass-fired plants). Despite transforming to renewable energy sources within power supply, natural gas is expected to remain an important energy source by 2050. Germany's industrial sector plays a substantial role in Germany with high emission levels that are hard to abate (iron and steel, refining, chemicals/petrochemicals, cement).

Storage potential in Germany is estimated at 95,000 Mt, with 75,000 Mt of storage in depleted oil & gas fields and 20,000 Mt of storage in aquifers. 80% of aquifers are situated in states that have banned carbon storage. Germany is not actively pursuing CCS, and no facilities are currently planned or under construction. National storage is expected to be limited going forward, partly indicated due to public scrutiny of onshore storage.

The relevance for storage in Denmark is deemed potentially high. Given public opposition to onshore storage and the limitation of CO2 storage on national territory, the export of German CO2 for storage is considered likely.

Below is an overview of the CCS potential in Germany.

Table 17: Summary of CCS potential in Germany[62]

SUMMARY OF CCS POTENTIAL		
Category	**Indicator**	**Comments**
CO2 emissions 2017 (MtCO2) Plants >100 ktCO2	406.2	CO2 emissions from largest point sources; mainly from power and heat generation industry, followed by iron and steel, cement, chemical and mineral oil and gas refinery industries
Co2 reduction targets	✓	• 2030: -55% from 1990 levels (national target) and -38% from 2005 levels (non-EU ETS)[63] • 2050: Climate neutral
National CCS focus/Support	◐	As Germany is Europe's highest emitter, CCS will probably need to play a significant role in Germany. Given the public opposition and the limitation of CO2 storage on national territory, the export of German CO2 for storage is deemed likely.
CCS targets	✗	No specific targets have been set for the deployment of CCS in Germany.
Total CCS Potential (MtCO2) 2022-2050	871	The largest share of capturable CO2 is expected to be derived from the power & heat sector (natural gas-fired power plants and biomass-fired plants). Significant potential also assessed within the industry (mainly iron and steel, refining, chemicals/petrochemicals, and cement).

[62] Global CCS Institute, "Global Status of CCS 2020"

[63] Germany's Integrated National Energy and Climate Plan (NECP 2030)

Own storage capacity (Mt)	95,000	75,000 Mt of storage in depleted oil & gas fields; 20,000 Mt of storage in aquifers. 80% of aquifers are situated in states that have banned carbon storage[64].
Own storage potential/support	◔	Germany is not actively pursuing CCS, and there are no CCS facilities in planning/construction. Additionally, public scrutiny of onshore storage indicates that national storage will be limited going forward.
Potential for DK storage	**High**	**Carbon storage outside of the country seems to likely, as the national storage of carbon is still controversial in Germany.**

4.2.4.2 CCS national targets and policies Germany

Germany is aiming to become climate neutral in 2050. As Germany is Europe's highest emitter, CCS will most likely need to play a significant role in Germany. While the German climate action programme highlights German initiatives that support CCS and CCU, it fails to substantiate a national commitment to technology uptake. Thus, the degree to which CCS will support the decarbonisation of industries has not been specified through CCS targets. However, the German integrated national energy and climate action plan explicitly gives room to the option of using carbon capture technology and notes that the majority of climate studies and scenarios confirm that CCS is indispensable for achieving net-zero emissions by 2050[65].

Until recently, Germany's had limited funding and support systems in place for the further development of CCS research and development projects. A CCS subsidy programme is currently being prepared, setting aside EUR 105 million for 2021 and, after that, EUR 120 million per year until 2025[66]. Aside from the programme under development, non-exclusive CCS programs have been in place, e.g., COORETEC focusing on coal-fired power with CCS, and Geotechnologien, which was a German R&D programme researching CO2 storage, which has now ended. The German NECP mentions the national "CO2-Win" and "CO2-Plus" programs as well as Germany's participation in the ERA-net EU Cofund ACT (Accelerating CCS Technologies) project as initiatives that will support research and the future application of CCU and CCS technologies, i.e. carbon separation, transport, storage and use[67]. In addition, Germany is currently preparing a subsidy programme aimed at supporting the country's raw material industry in developing technologies for CCU and CCS. The budget has been set at EUR 105 million for 2021 and, after that, an additional EUR 120 million per year until 2025[68].

Germany's regulatory framework related to CCS concerns the German CCS Act and the CO2 storage Act, both of which are integrated are based on the EU CCS directive in 2009. In 2012 the German CCS Act made onshore storage of CCS forbidden. The CCS Act halted all CCS projects except testing and demonstration pilots; no submissions were made. The storage Act restricts CO2 storage to only some parts of Germany, and the Federal States determine whether CO2 storage may take place based on several criteria. Additionally, storage activities are limited to those for which an application has been filed by December 2016 and to a maximum annual capacity of 1.3 MtCO2 per storage site. The total combined annual storage capacity for Germany is also limited to 4 MtCO2. However, the role of CCS in the future decarbonisation of the German economy became a point of discussion again after Chancellor Merkel stated in 2019 that CCS was necessary to achieve the ambitious climate targets.

Due to public acceptance issues and regulatory limits to onshore storage, tapping into the German onshore CO2 storage potential is most likely not politically feasible.

[64] European Commission, "On Implementation of Directive 2009/31/EX on the Geological Storage of Carbon Dioxide"
[65] Bundesministerium für Wirtshaft und Energie "Integrierter Nationaler Energie- und Klimaplan"
[66] Media Group: Germany Launches CCUS Support
[67] Bundesministerium für Wirtshaft und Energie "Integrierter Nationaler Energie- und Klimaplan"
[68] Media Group: Germany Launches CCUS Support

Table 18: CCS national targets and policies in Germany[69]

CCS NATIONAL TARGETS AND POLICIES		
Category	**Indicator**	**Comments**
Country CCS policy maturity/potential	◑	CCS recognised as a potentially important means of reaching climate targets. Yet, the lack of specific targets for CCS deployment and CCS restrictions in the legal framework creates a medium maturity level.
National CO2 reduction targets	✓	• 2030: -55% from 1990 levels (national target) and -38% from 2005 levels (non-EU ETS)[70] • 2050: Climate neutral
National CCS targets	✗	The Climate action programme names German initiatives supporting CCS and CCU but fails to substantiate a German commitment to the technology uptake.
CCS policies and legislations	—	The German CCS Act and the CO2 Storage Act are integrated and are based on the EU CCS directive in 2009. The Storage Act restricts CO2 storage to only some parts of Germany and sets limits to storage capacity. However, the role of CCS in the future decarbonisation of the German economy became a point of discussion again after former Chancellor Merkel stated in 2019 that CCS was necessary to achieve the ambitious climate targets.
CCS funding	—	A CCS subsidy programme is currently being prepared, setting aside EUR 105 million for 2021 and, after that, EUR 120 million per year until 2025[71]. However, until recently, support has been minimal, with a low level of R&D funding through non-exclusive CCS programs, e.g., COORETEC focusing on coal-fired power with CCS and Geotechnologien. The German NECP mentions the national "CO2-Win" and "CO2-Plus" programs as well as Germany's participation in the ERA-net EU project as initiatives that will support research and the future application of CCU technologies.
CCS storage-related policies	—	German CCS Act prohibits onshore storage of CCS. Due to public acceptance issues and regulatory limits to onshore storage, tapping into the German onshore CO2 storage potential is most likely not politically feasible.

4.2.4.3 CCS potential (capturable CO2 intended for storage) in Germany

Germany's energy sector remains one of the largest single sources of CO2 emissions in Europe. Emissions from large sources[72] are assessed at ~280 MtCO2 in 2017.

Today, energy in Germany is sourced predominantly by fossil fuels, followed by wind, nuclear power, solar, biomass (wood and biofuels) and hydro. As illustrated in Figure 3, supply is transforming towards heavier use of renewable energy sources in 2050; natural gas will remain an important energy source towards 2050.

Germany also has a substantial industrial sector with a high level of emissions (108.0 MtCO2 in 2017), including production and processing of iron and steel, refining, chemicals/petrochemicals, and cement.

The calculated capturable quantity of CO2 is estimated at on average 35 MtCO2/y between 2022 and 2040 and 49 MtCO2/y between 2041 and 2050, from close to 200 different large power and industrial processing facilities. The largest share of capturable CO2 is expected to be derived from the power & heat sector (natural gas-fired power plants and biomass-fired plants).

Within the industrial sector largest potential is assessed within the cement industry and refineries due to lacking alternatives to abate emissions, followed by other industries where CCS is relevant but only one option, i.e., chemical industry and iron & steel).

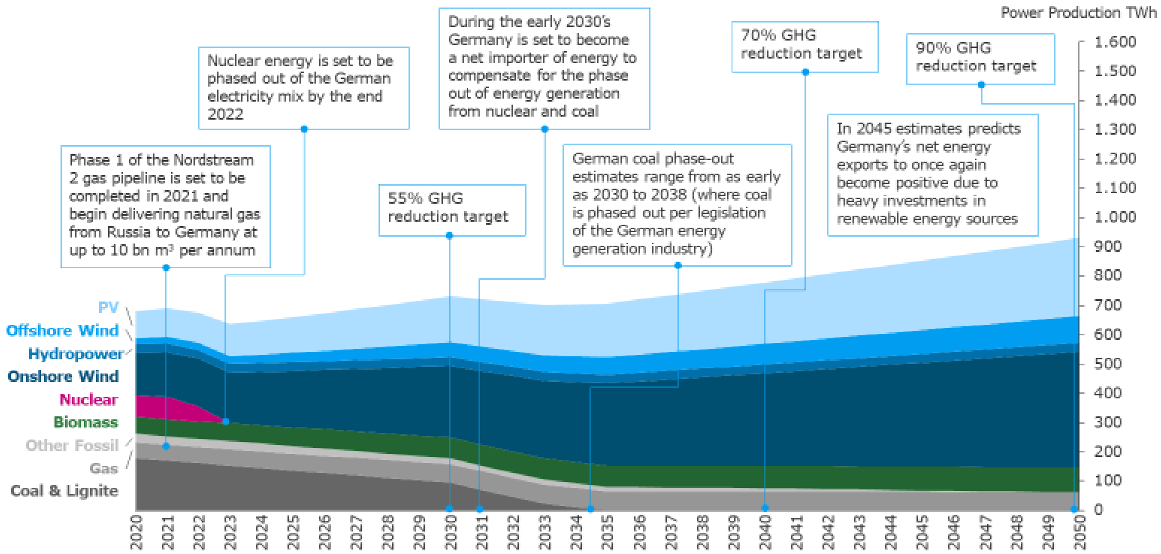
[69] Thema Consulting Group, "The role of carbon capture and storage in a carbon neutral Europe"; "Integrated National Energy and Climate Plan" of Germany; The European Commission, "Assessment of final national energy and climate plan of Germany"

[70] Germany's Integrated National Energy and Climate Plan (NECP 2030)

[71] Media Group: Germany Launches CCUS Support

[72] Plants with emissions exceeding 100,000 MtCO2/y

Figure 3: Germany's potential energy mix towards 2050



Source: Ramboll Analysis; EWI Research, "The energy market in 2030 and 2050 – The contribution of gas and heat infrastructure to efficient carbon emission reductions."

Table 19: CCS potential (intended for storage) in Germany

Sector	CO2 emissions 2017, MtCO2	Capturable quantity of CO2, MtCO2 (avg. MtCO2/y[73])		Comment
		2022-2040	2041-2050	
Power & Heat	**280.2**	**229** **(21)**	**339** **(34)**	• The overall significance of CCS within the German power & heat sector is low due to the focus on renewable power generation. However, the German government has expressed an interest in BECCS due to negative emissions compensating some industry and agricultural emissions hard to abate. Significance of CCS is also assessed to be high in case of non-recyclable and biogenic share of waste-to-energy and for emissions from natural gas-fired power plants • The capturable volume of CO2 intended for storage within the segment is estimated at up to ~36 MtCO2/y • The capturable quantities are evenly split between power plants fired on natural gas and those fired on biomass. However, the dynamics within these two segments are quite different. After an introduction around 2030, a capturable amount of CO2 from gas plants would quickly ramp up to comprise more than 50% of this industry by 2040. A further increase is expected towards 2050, as it is likely that only CCS-retrofitted plants will be allowed to operate. The overall share of capturable CO2 emissions from biomass-fired plants is expected to be much lower (~20%) but constant through the entire period (2030-2050) • CCS is not considered relevant for coal-driven plants since they will be phased out shortly after the CCS introduction

Industry	**108.0**	**154** **(14)**	**150** **(15)**	• Germany has a substantial industrial sector with a high level of emissions (108.0 MtCO2 in 2017), including production and processing of ferrous metals (28.6 Mt in 2017, mainly related to iron and steel), refining (21.1 MtCO2 in 2017), chemicals/ petrochemicals (24.6 Mt in 2017) and cement (25.0 MtCO2 in 2017)
				• The significance of CCS within the industrial sector varies across disciplines. It is assessed highest for cement processing and refining, where there are currently no other ways to reduce the process emissions significantly. Although switch of fossil fuels to biomass can reduce some emissions from cement processing, BECCS could still be an option to create negative emissions. Potential is also assessed within iron and steel, and chemicals. However, CCS is only one of several options on how to abate emissions (alternatives include electricity, green hydrogen and recycling). In general, the chemical industry is prioritizing CCU over CCS
				• According to Germany's Economy and Energy Ministry, around 30-40% of industrial emissions are process-linked and cannot be avoided using today's state of the art technology[74].
				• The total capturable volume intended for storage is estimated at up to ~18 MtCO2/y (peak between 2030 and 2040), and the highest potential is assessed within the mineral processing/cement industry. Ramp-up of the CCS within the industrial sector is expected to be relatively quick and reach the full potential already in 2035
				• CCS is also considered highly relevant for reducing CO2 emissions within:
				  ○ Chemical industry; Although the chemical industry is large in Germany, CCS is expected to be less prioritised than the alternative measures to abate emissions
				  ○ Iron and steel industry; Using hydrogen is an alternative (and high priority for the German government). Although the clear focus of the recently published Hydrogen Strategy is on green hydrogen production in- and outside of Germany (due to limited capacity/ability to produce enough green hydrogen, Germany is looking into collaborations with other countries), there are no provisions against the import and use of blue hydrogen[75]. Blue hydrogen is therefore expected to be a transitional solution, creating a need for CCS
				  ○ The gas refining industry; Given the long-term commitment to natural gas via the Nord Stream pipeline

Other	**18.8**	**-**	**-**	• No other significant potential areas have been assessed

[73] Average CO2 capturable amount is calculated for the time period 2030-2040

[74] The role of Carbon Capture and Storage in a Carbon Neutral Europe, Carbon Limits, 2020

[75] Federal Ministry of Economic Affairs and Energy – "Die Nationale Wasserstoffstrategie"

4.2.4.4 CO2 storage potential in Germany

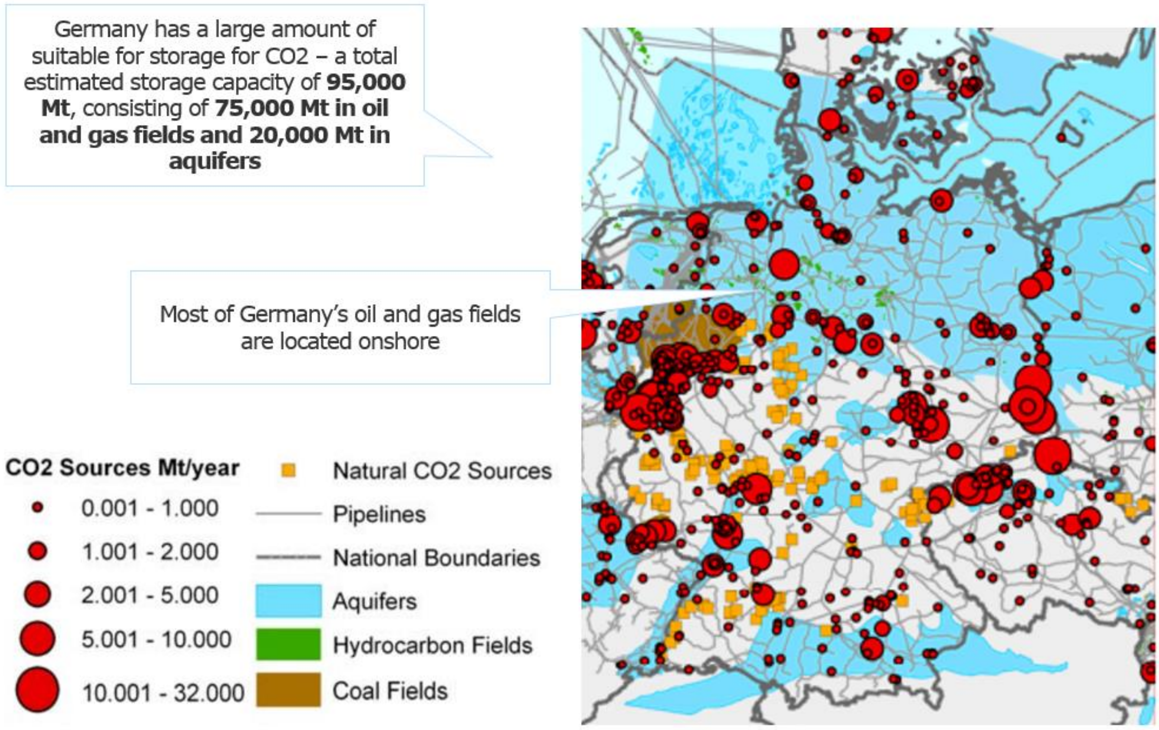
Germany's total CO2 storage capacity is 95,000 Mt, of which the majority – 75,000 Mt – is situated in oil and gas fields, and 20,000 Mt is situated in storage aquifers. Most of the German domestic carbon storage capacity is located onshore. The storage potential in the Baltic Sea is limited and virtually non-existent in the North Sea[76].

The German public has opposed onshore carbon storage, and as a result, only offshore carbon storage is currently legal, as described in section 4.2.4.2. No current or planned development projects of domestic carbon storage sites have been identified[77].

This means Germany does not have nor plan on developing domestic carbon storage capacity to cover upcoming CCS activity. However, due to the large amounts of captured carbon necessary to reach emissions reduction targets and the lack of plans for developing national storage, carbon export from Germany is deemed likely[78].

The picture below provides an overview of German storage site locations.

Figure 4: Overview of German carbon storage site locations



Source: Ramboll analysis, EU GeoCapacity, "Assessing European Capacity for Geological Storage of Carbon Dioxide"

76 DEA/Ramboll, "Catalouge of Geological Storage of CO2 in Denmark"

77 The Global CCS Institute, "Global status of CCS 2020"

78 Ramboll Expert

4.2.5 United Kingdom

4.2.5.1 Summary of CCS potential in the United Kingdom

The UK's emission is among the largest emitters of the analysed countries, with emissions from large stationary plants in 2017 at ~146 MtCO2.

The UK has created favourable conditions for the development and use of CCS through strong policy and regulatory support and dedicated action plants for CCS. Targets and commitments to CCS deployment at scale starting from the 2030s have been made, estimating >10 MtCO2 to be captured per year by 2030. CCS is a key part of the decarbonisation strategy to achieve carbon neutrality in 2050 in the UK, subject to costs coming down sufficiently. CCS will be of particular need in hard-to-abate industry sectors and decarbonisation of home-heating (hydrogen with CCS).

To support CCS research and projects extensive funding has been granted in the UK, e.g., 100 million GBP via Clean Growth Strategy funding to CCUS, BECCS and transport and storage of CO2, an additional 123 million GBP to R&D/innovation via UK CCS Research Centre), and with plans for further 1 billion GBP funding and revenue mechanisms.

CCS potential in the UK is high in both power & heat and industry; 1,986 MtCO2 in total between 2022 and 2050, and on average 50 MtCO2/y between 2022 and 2040 and 119 MtCO2/y between 2041 and 2050 for both the power & heat sector and the industry sector. CCS potential in the power & heat sector will primarily be in connection with hydrogen, in which CCS will be central to support this. Within the industry, potential is in hard-to-abate industries, i.e., mineral oil & gas refineries, mineral production (cement, lime and plaster), iron and steel production, chemicals production, as well as food production.

The UK has significant storage capacity, estimated at 69,000 Mt of storage in aquifers and 9,000 Mt of storage in depleted oil & gas fields. Storage is permitted in the offshore area.

The relevance for storage in Denmark is deemed low, as the UK has already invested in CCS technology, initiated storage projects, developed CCS deployment timelines and expect CCS to be key to reaching net zero emissions.

Below is an overview of the CCS potential in the UK.

Table 20: Summary of CCS potential in United Kingdom

SUMMARY OF CCS POTENTIAL		
Category	**Indicator**	**Comments**
CO2 emissions 2017 (MtCO2) Plants >100 ktCO2	146.3	CO2 emissions from large point sources; primarily from the power and heat generation industry followed by refineries and chemical production facilities.
CO2 reduction targets	✓	• 2030: -68% from 1990 levels[79] (economy wide emissions) • 2050: Net zero emissions
National CCS focus/Support	◕	Strong policy and regulatory support, as well as dedicated actions plans for CCS, create favourable conditions for the development and use of CCS in the UK. An extensive national support system is in place, granting 100 million GBP via Clean Growth Strategy to CCUS, BECCS and transport and storage of CO2. Additional GBP 123 million to R&D via UK CCS Research Centre and plans for further GBP 1 billion funding and revenue mechanisms have been announced.
CCS targets	✓	The UK is committed to deploying CCS at scale during the 2030s, subject to costs coming down sufficiently. The UK's target is to capture >10 MtCO2/y by 2030, and capture and store ~0.32 tCO2 per capita. Between 2023-2032, the government estimates that driving the growth of low hydrogen could deliver savings of ~40 MtCO2e, equivalent to 9% of 2018 UK emissions.[80] By 2050, ~60% of the carbon captured in the

[79] https://www.gov.uk/government/news/uk-sets-ambitious-new-climate-target-ahead-of-un-summit

[80] HM Government "The Ten Point Plan for a Green Industrial Revolution"

		UK has been estimated to be in the greenhouse gas removals sector[81].
Total CCS Potential (MtCO2) 2022-2050	1,986	Both within power & heat sector (in connection with hydrogen) and industry (mineral oil & gas refineries, mineral production, iron and steel production, chemicals production, as well as food production)
Own storage capacity (Mt)	78,000[82]	69,000 Mt of storage in aquifers; 9,000 Mt of storage in depleted oil & gas fields
Own storage potential/support		The UK is actively developing and investing in offshore storage sites as a part of the climate strategy which has the support of the public[83]
Potential for DK storage	**Low**	**Low significance for DK; UK has significant storage capacity and already developed invested in CCS technology, initiated offshore storage projects, implemented CCS deployment timelines and believe CCS to be key for reaching net-zero.**

4.2.5.2 CCS national targets and policies in the United Kingdom

The UK aims to become carbon neutral in 2050 and emphasises CCS as a key decarbonisation strategy to achieve carbon neutrality. The UK's 'Clean Growth Strategy' of 2017 includes CCS as a specific approach to decarbonisation, setting forth an approach to enable the UK to become a global technology leader for CCUS and ensure that government has the option of deploying CCUS at scale during the 2030s[84]. CCS is recognised as an essential technology to reduce emissions from especially industry sectors and to decarbonise home-heating (hydrogen with CCS). However, the strategy notes that the cost of CCS will have to come down for it to be deployed at scale in the UK. In 2018, the UK Government's 'Carbon Capture Usage and Storage Deployment Pathway' set out further details on the steps it plans to take to deploy CCUS at scale during the 2030s, subject to the costs coming down sufficiently[85]. The Government's "10 Point Action Plan for a Green Industrial Revolution", announced in November 2020, also includes CCUS as a necessary point to decarbonise hard to abate sectors and reach negative emissions[86]. In December 2020, the UK's Climate Change Committee, acting as the government's climate advisers, have proposed a legally binding "carbon budget" that is in line with the national target of "net-zero" emissions by 2050, in which all pathways explored see the use of CCS as a critical and cost-effective means of meeting the UK's 2050 Net Zero target[87].

The UK has set a specific target for CCS deployment in 2030. The UK's CCS target is to capture >10 MtCO2/y by 2030[88]. The Climate Change Committee estimates that by 2030, CCS per capita will reduce UK emissions by 0.32 tCO2/person/year[89]. Further, the estimated savings between 2023-2032 from the deployment of low-carbon hydrogen are ~40 MtCO2e. By 2050, ~60% of the carbon captured in the UK has been estimated to be in the greenhouse gas removals sector, primarily through the combustion of biomass for electricity generation, with a further 20% used for the production of hydrogen and 10% used with gas in the power sector. Bioenergy with carbon capture and storage (BECCS) facilities have been estimated by the UK's Climate Change Committee to remove 22 MtCO2/y from the atmosphere by 2035 and 53 MtCO2/y by 2050[90]. The Committee estimates that Direct Air Capture of CO2 with storage (DACCS) starts to scale up from 2040 to reach 5 MtCO2/y by 2050.

The UK has an extensive national support system for CCS in place. CCS funding has been granted through the Clean Growth Strategy, allocating GBP 100m for CCUS applications in low-carbon hydrogen production, BECCS, as well as transport and storage of CO2. In addition, GBP 125m was allocated to an R&D and innovation program, which established UK CCS Research Centre. In

[81] Climate Change Committee "The Sixth Carbon Budget - The UK's plan to net zero"
[82] Department of Energy & Climate Change "CCS Roadmap Supporting deployment of Carbon Capture and Storage in the UK"
[83] Edie "Survey: Two-thirds of Brits support UK's green industrial revolution plans"
[84] HM Government "Clean Growth: The UK Carbon Capture Usage and Storage deployment pathway: An Action Plan"
[85] HM Government "The Clean Growth Strategy Leading the way to a low carbon future"
[86] HM Government "The Ten Point Plan for a Green Industrial Revolution"
[87] Climate Change Committee "The Sixth Carbon Budget - The UK's plan to net zero"
[88] HM Government "The Ten Point Plan for a Green Industrial Revolution"
[89] Climate Change Committee "The Sixth Carbon Budget - The UK's plan to net zero"
[90] Climate Change Committee "The Sixth Carbon Budget - The UK's plan to net zero"

2017, the Centre was awarded an additional GBP 6.1m to fund research work on CCS through 2022. In 2020, the government further committed to establishing a GBP 1 billion CCUS Infrastructure Fund, and in 2021, aims to introduce a revenue mechanism to bring through private sector investment in industrial carbon capture and hydrogen projects to provide the certainty investors require[91]. Further, the Scottish Government's strategy allocates GBP 60m to the Low Carbon Innovation Fund, as well as GBP 20m to the Energy Investment Fund. Additionally, the UK government has supported several frontend engineering, and design (FEED) studies for CCS in the UK (e.g., Peterhead and Longannet).

The UK is one of the leading nations in terms of policy support for CCS with a strong institutional framework and a range of climate change mitigation policies such as emission performance standards and a carbon price floor. The UK's comprehensive legal and regulatory CCS framework addresses the full chain of the CCS project life cycle. The Energy Act 2008 and its accompanying Carbon Dioxide Licensing Regulations 2010 transpose the requirements of the EU Storage Directive and establish the UK's framework for offshore CO2 storage activities. The regime applies to storage in the offshore area comprising both UK territorial sea and beyond designated as a gas importation and storage zone (GISZ) under section 1(5) of the Act. In addition, the UK has ratified the London Protocol that allows CO2 export to other states for storage purposes.

Table 21: CCS national targets and policies in the United Kingdom

CCS NATIONAL TARGETS AND POLICIES IN UNITED KINGDOM		
Category	**Indicator**	**Comments**
Country CCS policy maturity/potential	●	The policy maturity is considered high due to CCS strategies and targets, strong policy and legislative frameworks and financial support, creating favourable conditions for CCS.
National CO2 reduction targets	✓	• 2030: -68% from 1990 levels[92] (economy wide emissions) • 2050: Net zero emissions
National CCS targets	✓	The UK is committed to deploying CCS at scale during the 2030s, subject to costs coming down sufficiently. The UK's target is to capture >10 MtCO2/y by 2030 and capture and store ~0.32 tCO2 per capita.
CCS policies and legislations	✓	The UK is one of the leading nations in terms of policy support for CCS with a strong institutional framework in place and a range of climate change mitigation policies such as emission performance standards and a carbon price floor. CCS legislation comprises The Energy Act 2008 and its accompanying regulations which transpose the requirements of the EU Storage Directive and establish the UK's framework for offshore CO2 storage activities.
CCS funding	✓	Extensive funding dedicated to CCS research and projects has been granted in the UK.
CCS storage-related policies	✓	Storage permitted in the offshore area comprising both UK territorial sea and beyond designated as a gas importation and storage zone (GISZ) under section 1(5) of the Act.

4.2.5.3 CCS potential (capturable CO2 intended for storage) in the United Kingdom

The UK is one of the largest emitters of the countries, with emissions from large stationary plants estimated at ~146 MtCO2 in 2017, of which the power sector comprises 109.6 MtCO2 and the industry 33.2 MtCO2.

At present, energy is sourced from primary oil (crude oil and natural gas liquids), natural gas, primary electricity (consisting of nuclear, wind, solar and natural flow hydro), bioenergy and waste, and a very small amount of coal (1%)[93]. The UK power and heat sector have been transforming already from the 2020s towards increased supplies of low-carbon electricity

[91] HM Government "The Ten Point Plan for a Green Industrial Revolution"

[92] https://www.gov.uk/government/news/uk-sets-ambitious-new-climate-target-ahead-of-un-summit

(renewables and nuclear) and hydrogen, where CCS will be a central support vehicle to those supplies[94].

The industry comprises mineral oil & gas refineries, mineral production (cement, lime and plaster), iron and steel production, chemicals production, as well as food production, where high CCS potential is deemed due to CCS regarded as a key solution to decarbonise these hard to abate emissions.

All of the scenarios outlined by the CCC critically incorporate CCS since it is considered a cost-efficient means of meeting the UK's 2050 Net-zero target, and the deployment of CCS is already beginning from 2025[95]. The calculated capturable quantity of CO2 is estimated at on average 50 MtCO2/y between 2022 and 2040 and 119 MtCO2/y between 2041 and 2050 for both the power & heat sector and the industry sector.

[94] Committee on Climate Change (CCC), "Net Zero. The UK's contribution to stopping global warming"

[95] Gov.uk, "UK ENERGY IN BRIEF 2020"

Table 22: CCS potential (intended for storage) in the United Kingdom

Sector	CO2 emissions 2017, MtCO2	Capturable quantity of CO2, MtCO2 (avg. MtCO2/y[96])		Comment
		2022-2040	2041-2050	
Power & Heat	**109.6**	**518.4** **(32.4)**	**798.8** **(79.9)**	• The overall significance of CCS within the UK power sector is considered to be widespread due to the UK's energy sector transformation towards increased supplies of low-carbon electricity (renewables and nuclear) and hydrogen, where CCS will be a central support vehicle to those supplies[97] • Power and heat CO2 in the United Kingdom splits into thermal power and heat generation (99.7 MtCO2) and waste-to-energy plants (9.9 MtCO2) • The capturable volume of CO2 intended for storage within the segment is estimated at up to 90 MtCO2/y, including BECCS: - Based on scenario studies CCS from fossil power generation can range between 22-51 MtCO2 in 2050, and Ramboll estimates the median of the two in 2050, i.e. 36 MtCO2 - BECCS will play a significant role for new WtE plants and extensions where CCS should be built, and all energy-from-waste plants should fit CCS by 2050, starting from 2040. BECCS from the power industry as a whole is expected to range between 11-25 MtCO2/y in 2050, for which Ramboll also assumes the median; 18 MtCO2/y - Further, there is an important role for hydrogen produced from fossil gas with CCS in the medium term to enable hydrogen growth. Thus CCS from the production of hydrogen has potential and is estimated to range between 22-50 MtCO2/y in 2050, where Ramboll applies the median (36 MtCO2/y) • The introduction of CCS is expected from 2025, and the most rapid emissions reduction increases are estimated from 2025-2035, therefore the increase of CCS potential is the steepest between this period[98]. From 2035-2050 the CCS potential continues to rise but at a slower pace: Following the 2024 coal phase-out, gas-fired power without CCS should be phased out by 2035 and any gas plant built before 2030 should be made ready for a switch to CCS or hydrogen, which is why the deployment of CCS keeps increasing towards 2050
Industry	**33.2**	**278.8** **(17.4)**	**390.3** **(39.0)**	• The UK produces notable levels of emissions in the industry sector, including mineral oil & gas refineries, mineral production (cement, lime and plaster), iron and steel production, chemicals production, as well as food production • In the industry sector, CCS faces competition from hydrogen, electrification and CCU. However, CCS is considered to comprise the majority of engineered greenhouse gas removals in 2050. The significance of CCS is high within the industry sector since CCS is considered the key deep decarbonisation option for manufacturing, oil refineries, cement and steel production. • Total capturable volumes intended for CCS excluding BECCS are aligned with the CCC high case of about 24 MtCO2/y in 2050: - CCS is applied to the manufacturing sector at scale in the 2030s and continues to remove CO2 at similar levels out to 2050 - CCS is also applied to half of the UK's integrated steelwork capacity in the early 2030s - CCS will play a significant role in binging emissions down for cement, lime and other mineral sites - Oil refineries emissions are also abated through CCS, along with reduced oil demand and energy efficiency improvements. CCS is the main emissions reduction measure for the remaining emissions from oil refineries • BECCS from the industry sector is expected to range between 11-25 MtCO2/y in 2050, of which Ramboll estimates the median in 2050, i.e. 18 MtCO2/y

[96] Average CO2 capturable amount is calculated for the time period 2030-2040

[97] Committee on Climate Change (CCC), "Net Zero. The UK's contribution to stopping global warming"

[98] Climate change committee, "The Sixth Carbon Budget. The UK's path to Net Zero"

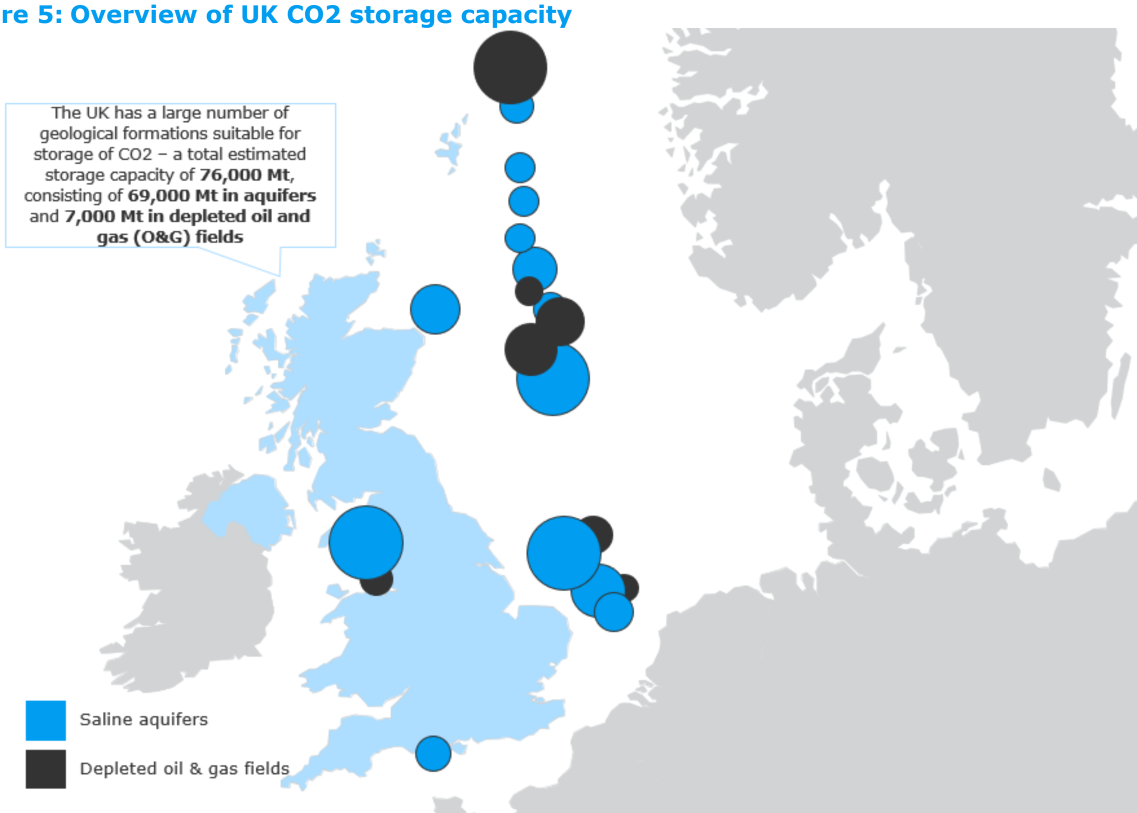
4.2.5.4 CO2 storage potential in the United Kingdom

The UK's total CO2 storage capacity is assessed at 78,000 Mt. The majority, 69,000 Mt, is situated in storage aquifers, and 9,000 Mt is situated in oil and gas fields units. Most of the aquifer storage capacity is located on the United Kingdom continental shelf relatively far offshore in the North Sea near the oil and gas fields. Oil and gas fields can be cheaper to develop than aquifer storage units as some of the offshore infrastructures is already in place[99].

The UK public has a positive attitude towards utilising domestic offshore carbon storage capacity[100]. UK's storage capacity is considered to be sufficient to cover all upcoming CCS activity.

The picture below provides an overview of UK storage site locations and their relative sizes.

Figure 5: Overview of UK CO2 storage capacity



Source: Ramboll analysis, EU Geocapacity, "Assessing European Capacity for Geological Storage of Carbon Dioxide"; Costain, Energy Technologies Institute, Pale Blue Dot, Axis Well Technology, "Progressing Development of the UK's Strategic Carbon Dioxide Storage Resource: A summary of result from the strategic UK CO2 storage appraisal project

[99] IOGP, "The potential for CCS and CCU in Europe"

[100] Edie, "Two thirds of Brits support UK's green industrial revolution plans"

4.2.6 The Netherlands

4.2.6.1 Summary of CCS potential in the Netherlands

The Netherlands' CO2 emissions from large sources in 2017 were ~95 MtCO2. Most emissions relate to the power and heat sector (~65 MtCO2) and industrial production and processing (~30 MtCO2).

The Netherlands is aiming to reduce CO2 emissions by 95% from 1990 levels by 2050. CCS is acknowledged in the Netherlands for its important role in reaching the climate target, yet mostly as a transition solution until CCU and CCS linked with bioenergy can replace current CCS solutions for fossil fuel industries. A CCS target has been set to 7.2 MtCO2/y by 2030, which is about half of the country's industry CO2 emissions reduction target of 14.3 MtCO2/y. Thus, CCS plays a considerable role in the reduction of CO2 emissions from industry, yet it is controlled since subsidies for CCS is capped at 7.2 MtCO2/y and subsidised are made available only if no other cost-effective CO2-reduction alternatives are available, and finally, after 2035, no new subsidies are granted to fossil CCS projects. The latter limitation is to ensure that the fossil fuel industry does not continue in the future. According to national policies, CCS is initially limited to industry sectors (steel, refinery, hydrogen, fertilizer, waste incineration)[101]. Despite ambitious climate targets, the Netherlands is currently behind most other EU countries with respect to their renewable energy targets, i.e., the country's share of energy coming from renewable sources is the lowest in the EU.

National support for CCS has been granted through various R&D-related funding and going forward; subsidies will be granted to a broader set of technologies to avoid CO2 emissions, including CCS through The Sustainable Energy Transition Incentive Scheme (SDE++).

CCS potential in the Netherlands is estimated at 274 MtCO2 between 2022 and 2050 and on average 12 MtCO2/y between 2022 and 2040 and 15 MtCO2/y between 2041 and 2050, with the largest share from the power & heat sector. Gas is still expected to be part of the Dutch energy mix towards 2050, and CCS will play an important role to abate CO2 emissions from this source. Industrial sector emissions mainly relate to chemicals and refineries and will be highest in the short-medium run, as in the long run, the government is expected to prioritize CCU and CCS linked with bioenergy.

Storage potential in the Netherlands is estimated at 4,000 Mt, with 3,000 Mt of storage in depleted oil & gas fields and 1,000 Mt of storage in aquifers. Storage is only allowed offshore or in other countries.

The relevance for storage in Denmark is deemed medium. It is uncertain how much the Netherlands expects to store nationally. The Netherlands has identified the risk that CO2 transport demand might exceed the storage capacity in their CO2TransPorts industry cluster project[102]. Additionally, there could be opportunities for export of Dutch CO2 if their national CCS projects delay (the country has a history of delay with previous renewable energy projects), and finally, The Dutch government has acknowledged that it will be challenging for The Netherlands to achieve emissions reduction by scaling up renewables and thus, CCS could be a potential source to make up for this potential gap[103]. Therefore, it is possible that Netherlands will not be able to meet the CO2 demand with national storage capacity in time and will need to export CO2, at least in the short-medium term.

Below is an overview of the CCS potential in the Netherlands.

[101] The Dutch Ministry of Economic Affairs & Climate Policy: Clean Energy Solutions Center – "Carbon Capture, Utilization and Storage in The Netherlands (Webinar)"

[102] European Commission, "Candidate PCI projects in cross-border carbon dioxide transport networks"

[103] IEA – The Netherlands 2020 Energy Policy Review

Table 23: Summary of CCS potential in the Netherlands

SUMMARY OF CCS POTENTIAL		
Category	**Indicator**	**Comments**
CO2 emissions 2017 (MtCO2) Plants >100 ktCO2	95.0	CO2 emissions from largest point sources; mainly by from the power and heat generation industry, followed by the chemical production and mineral oil and gas refinery industries
CO2 reduction targets	✓	• 2030: -49% from 1990 levels (national target) and -36% from 2005 levels (non-EU ETS)[104] • 2050: -95% from 1990 levels (national target)
National CCS focus/Support	◕	The Netherlands recognizes the important role CCS will have in reaching CO2 reduction targets, yet mostly as a short-term solution until CCU and CCS linked with bioenergy can replace current CCS solutions.
CCS targets	✓	The Netherlands initially planned to capture and store 18 MtCO2/y by 2030, but the target has been adjusted to 7.2 MtCO2/y, as few believed the initial goal to be realistically achievable.[105] CCS is estimated to account for 20 mtCO2 reductions by 2030 from industrial sectors.[106]
Total CCS Potential (MtCO2) 2022-2050	274	Evenly split between power & heat (natural gas emissions) and industry (emissions from chemicals processing and refineries).
Own storage capacity (Mt)	4,000[107]	3,000 Mt of storage in depleted oil & gas fields; 1,000 Mt of storage in aquifers
Own storage potential/support	◑	Storage of CO2 is only allowed offshore or in other countries but supported by the government through several projects.[108]
Potential for DK storage	**Medium**	**Medium significance for DK storage due to ongoing national carbon storage site development. However, uncertainty remains regarding project delays and storage capacity, preventing NL from reaching GHG targets in the next 10-20 years, making carbon export a possibility in the future.**

4.2.6.2 CCS national targets and policies the Netherlands

The Netherlands is aiming to reduce CO2 emissions by 95% from 1990 levels by 2050. The Netherlands has a favourable policy- and regulatory environment for the uptake of CCS, as is seen by the government indicating CCS as a necessary instrument to reduce CO2 emissions in the short term.[109] However, in the long term, the government wants to move away from CCS of fossil fuel emissions towards CCU and CCS linked with bioenergy.[110]

The Netherlands has set CCS targets limited to the industry sector, initially planning to capture and store 18 MtCO2/y by 2030, but the target has been adjusted to 7.2 MtCO2/y, as few believed the initial target to be realistically achievable[111]. By 2030, CCS has been estimated to account for 20 mtCO2 reductions from industrial sectors[112].

Policy measures are in place to support the deployment of CCS in the Netherlands. The government is preparing to release a new Dutch CCS Roadmap that is expected to accelerate the deployment of CCS.[113] In 2019, the Dutch government decided, on top of the ETS system, to implement a carbon tax, which could provide additional incentive for large emitters to implement CCS.

[104] The Netherland's Integrated National Energy and Climate Plan (NECP 2030)
[105] CE Delft "Feasibility study into blue hydrogen – technical, economic and sustainability analysis", July 2018
[106] Global CCS Institute CO2RE database
[107] GEUS "Assessment of CO2 Storage Potential in Europe"
[108] International Energy Agency "The Netherlands 2020: Energy Policy Review"
[109] Klimaat-akkoord "Voorstel voor hoofdlijnen van het Klimaatakkoord"
[110] International Energy Agency "The Netherlands 2020: Energy Policy Review"
[111] CE Delft "Feasibility study into blue hydrogen – technical, economic and sustainability analysis", July 2018
[112] Global CCS Institute CO2RE database
[113] Global CCS Institute CO2RE database

In recent years, the Dutch Government has supported CCS R&D initiatives through CATO, which is a national CCS R&D program that involves collaboration and funding from both the government and industry.[114] The Sustainable Energy Transition Incentive Scheme (SDE++) of 2020 is a key funding source as it awards subsidies to a broader set of technologies to avoid CO2 emissions, including CCS. The government is expecting that a significant share of industrial emissions reductions will be realised through SDE++ support for CCS and low-carbon hydrogen.[115] The scheme sets a limit of 7.2 MtCO2/y for subsidising industrial CCS. A carbon storage project called Porthos is expected to be granted funding from the SDE++ scheme in 2022.

The Netherlands has developed an integrated and comprehensive legal framework for CCS activities, which draws upon wider national environmental and mining laws. The Dutch government has mainly implemented the requirements of the EU storage Directive through amendments to the national mining legislation, notably the Mining Decree and Mining Regulation. In addition, the Netherlands has ratified the London Protocol that allows CO2 export to other states for storage purposes.

Under the Dutch Mining Act, underground storage of CO2 is only allowed offshore or in other countries.[116] To unlock storage potential, regulatory changes on the transfer of ownership and decommissioning of the gas field after they have been depleted are necessary. These regulatory aspects have been identified as potential barriers to the development of CCS projects in the Netherlands.

Table 24: CCS national targets and policies in the Netherlands

CCS NATIONAL TARGETS AND POLICIES		
Category	**Indicator**	**Comments**
Country CCS policy maturity/potential	◕ (three-quarter filled circle)	Strong policy and regulatory framework to support CCS and specific targets for CCS deployment create favourable policy conditions for CCS in the Netherlands, yet mostly in the short-term.
National CO2 reduction targets	✓	• 2030: -49% from 1990 levels (national target) and -36% from 2005 levels (non-EU ETS)[117] • 2050: -95% from 1990 levels (national target)
National CCS targets	✓	The Netherlands initially targeted to capture and store 18 MtCO2/y by 2030, but the target has been adjusted to 7.2 MtCO2/y from the industrial sector.[118] By 2030, CCS is estimated to account for 20 MtCO2 reductions from industrial sectors.[119]
CCS policies and legislations	✓	CCS is regarded as a necessary instrument to reduce CO2 emissions in the short term[120], but in the long term, the government wants to move away from CCS of fossil fuel emissions towards CCU and BECCS.[121] The Netherlands has developed an integrated and comprehensive legal framework for CCS activities, which draws upon wider national environmental and mining laws.
CCS funding	✓	Support systems and funding for CCS research and projects are in place in the Netherlands, most notably through the national CCS R&D programme CATO. The more recent funding source available for CCS is the SDE++, which is a pivotal funding source for CCS in the Netherlands. A carbon storage project called Porthos is expected to be granted funding for the SDE++ scheme in 2022.
CCS storage-related policies	—	Underground storage of CO2 is only allowed offshore or in other countries.[122] To unlock storage potential and prevent the development of CCS projects in the Netherlands, regulatory

[114] Global CCS Institute CO2RE database
[115] International Energy Agency "The Netherlands 2020: Energy Policy Review"
[116] International Energy Agency "The Netherlands 2020: Energy Policy Review"
[117] The Netherland's Integrated National Energy and Climate Plan (NECP 2030)
[118] CE Delft "Feasibility study into blue hydrogen – technical, economic and sustainability analysis", July 2018
[119] Global CCS Institute CO2RE database
[120] Klimaat-akkoord "Voorstel voor hoofdlijnen van het Klimaatakkoord"
[121] International Energy Agency "The Netherlands 2020: Energy Policy Review"
[122] International Energy Agency "The Netherlands 2020: Energy Policy Review"

		changes on the transfer of ownership and decommissioning of the gas field after they have been depleted are necessary.

4.2.6.3 CCS potential (capturable CO2 intended for storage) in the Netherlands

Total CO2 emissions from large sources[123] in the Netherlands were ~95 MtCO2 in 2017, of which ~65 MtCO2 were related to the power & heat sector and ~30 MtCO2 to the industrial production and processing.

The overall significance of CCS within the Dutch power & heat sector is considered medium.

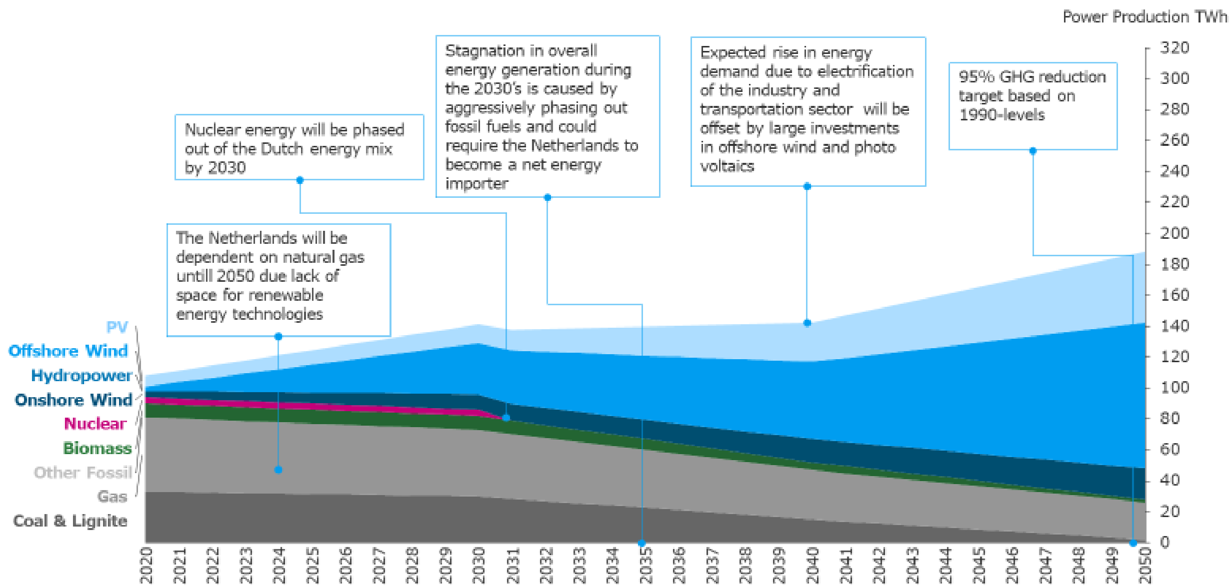
Despite the very ambitious targets for climate-change mitigation, the Netherlands today is currently furthest behind other EU countries in the production of energy from renewable sources, e.g., they fell short of their onshore wind target of 6 GW in 2020 due to public acceptance, grid constraints (require a confirmation from relevant network operators) and land fees, whereas large-scale PV projects were delayed since the supporting grid infrastructure was not delivered in time for when the PV construct was finished. Renewable energy in the Netherlands comes mainly from biofuels, waste, and wind, while geothermal, solar and hydro energy play only a minor role in the country.

Despite plants phasing out production at Groningen, Europe's largest onshore natural gas field, by 2022, it is expected that the gas will still be part of the Dutch energy mix towards 2050.

Emissions for the industrial sectors have mainly concentrated around chemicals and refineries. While significant potential is assessed with regards to refineries, the chemicals sector is expected to prioritise other alternatives, including CCU, in the long run.

The calculated capturable quantity of CO2 is estimated at on average 12 MtCO2/y between 2022 and 2040 and 15 MtCO2/y between 2041 and 2050.

Figure 6: The Netherland's potential energy mix towards 2050



Source: Ramboll Analysis; Alliander, ECN, "The supply of flexibility for the power system in the Netherlands, 2015-2050"

Table 25: CCS potential (intended for storage) in the Netherlands

Sector	CO2 emissions 2017, MtCO2	Capturable quantity of CO2, MtCO2 (avg. MtCO2/y[124])		Comment
		2022-2040	2041-2050	
Power & Heat	**64.6**	**75** **(5)**	**95** **(9)**	• The overall significance of CCS within the Dutch power & heat sector is considered medium, as the Netherlands is challenged to convert all its energy production to renewable sources • The capturable volume of CO2 intended for storage within the segment is estimated at up to ~9 MtCO2/y, and mainly related to the gas-fired plants • CCS is not considered relevant for coal-driven plants since they will be phased out shortly after the CCS introduction
Industry	**29.9**	**79** **(5)**	**51** **(5)**	• Emission from the industrial sector was 29.9 MtCO2 in 2017, including production and processing of chemicals/ petrochemicals (16.9 Mt in 2017) and refineries (10.6 MtCO2 in 2017) • The significance of CCS within the industrial sector varies across disciplines. It is high for refineries but much lower for the chemicals industry, where there are several options to abate emissions. In general, the chemical industry is prioritizing CCU over CCS • The total capturable volume intended for storage is estimated at up to ~5 MtCO2/y; The Netherlands has indicated CCS as a necessary instrument to reduce CO2 emissions in the short term. In the long term, the government wants to move away from CCS of fossil fuel emissions towards CCU and CCS linked with bioenergy. Consequently, CCS within the industrial sector is expected to peak between 2030 and 2045 and slightly decrease thereafter.
Other	**0.5**	**-**	**-**	• No other significant potential areas have been assessed

[124] Average CO2 capturable amount is calculated for the time period 2030-2040

4.2.6.4 CO2 storage potential in the Netherlands

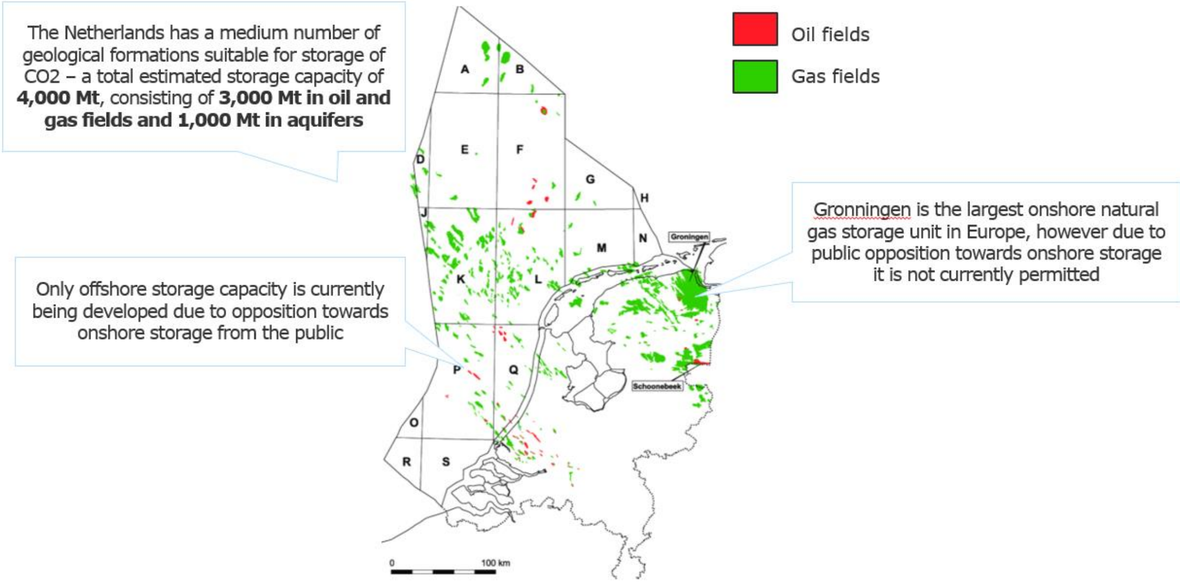
The Netherlands has a total of 4,000 Mt of storage capacity – 3,000 Mt – in oil and gas fields and 1,000 Mt in aquifers[125]. As described in section 4.2.6.2, carbon storage is only allowed offshore, which corresponds to 1,000 Mt of storage capacity in oil and gas fields and 700 Mt in offshore aquifer storage capacity[126].

While the Netherlands is developing projects to store carbon domestically, industry cluster projects acknowledge that the demand for storing CO2 might exceed the storage capacity and especially if the CCS project deliveries are faced with delays[127]. This means that the export of captured carbon to international carbon storage sites could be necessary for the short-to-medium term.

Despite Government support for CCS and their continued efforts to support CCS and set targets, CCS was a controversial topic during the 2019 climate agreement negotiations; It was opposed by several NGOs and some political parties[128]. Nevertheless, a study of public opination towards CCS showed the Dutch public a neutral attitude towards offshore CCS[129].

The picture below provides an overview of possible carbon storage sites in the Netherlands.

Figure 7: Overview of CCS facilities in Netherlands



Source: Ramboll analysis, Vrije Universiteit Amsterdam, Jan de Jager, "Petroleum Geology of the Netherlands"

[125] GEUS, "Assessment of CO2 Storage Potential in Europe"

[126] Noordzeeloket, "CO2-storage"

[127] European Commission, "Candidate PCI projects in cross-border carbon dioxide transport networks"

[128] The Dutch Ministry of Economic Affairs & Climate Policy: Clean Energy Solutions Center – "Carbon Capture, Utilization and Storage in The Netherlands (Webinar)"

[129] Centre for Energy and Environmental Studies, Dept. of Psychology, Leiden University, "Informed public opinion in the Netherlands: Evaluation of CO2 capture and storage technologies in comparison with other CO2 mitigation options"

4.2.7 Poland

4.2.7.1 Summary of CCS potential in Poland

Poland's emissions from large sources in 2017 were ~167 MtCO2. Most emissions relate to the power & heat sector (121 MtCO2), and the remaining to industrial production and processing (22 MtCO2) and other activities (23 MtCO2), including coal mining, landfill etc.

Poland is the only country where the Government has not yet committed to becoming carbon neutral of all the ten countries and the EU countries. However, the climate ministry presented an update of the country's 2040 energy roadmap at the end of 2020, where the country formally endorses the EU 2050 climate neutrality goal. Poland does not actively pursue CCS at present. However, the outlook for its coal expansion plans provide opportunities for carbon removal for Poland to reach the EU commitments.

CCS potential in Poland is estimated at 591 MtCO2 between 2022 and 2050 and on average 19 MtCO2/y between 2022 and 2040 and 34 MtCO2/y between 2041 and 2050, with the largest share coming from the power & heat sector. To decarbonise the Polish power & heat sector, CCS and BECCS are expected to be necessary. Although most of the existing plants are old, CCS will be relevant for some of the newer current power & heat plants (coal and biomass CHP) and upcoming natural gas (to be built by 2035). Further, CCS is expected to play a role in the decarbonising industrial sector, specifically, iron and steel (in connection with the use of blue hydrogen) and mineral/cement industry, where CCS is currently the only relevant option for emissions abatement.

Storage potential in Poland is estimated to be 78,000 Mt, mainly in aquifers. Only offshore storage can currently be developed (CO2 storage is banned until 2024 except for offshore demonstration projects). However, no development projects have been registered, and Poland has shown limited interest in national storage. While Poland's domestic storage capacity can cover all upcoming CCS activity needs until 2050, it is expected that only some of the upcoming CCS activity will be covered by domestic storage capacity. Nonetheless, with potential EU funding Poland may become interested in national storage, especially since the high cost of exporting CO2 might be high.

The relevance for storage in Denmark is deemed medium, as limited interest in national storage and large CCS potential could make CO2 export relevant.

Below is a summary table of the CCS potential in Poland.

Table 26: Summary of CCS potential in Poland

SUMMARY OF CCS POTENTIAL		
Category	**Indicator**	**Comments**
CO2 emissions 2017 (MtCO2) Plants >100 ktCO2	166.7	CO2 emissions from the largest point sources; mainly from the power and heat generation industry powered by old coal plants, followed by the cement, iron and steel industries
Co2 reduction targets	✓	• 2030: -21% in EU ETS sectors and -7% from 2005 levels (non-EU ETS) (-30% from 1990 levels)[130] 2050: -85-90% from 1990 levels
National CCS focus/Support	◔	Poland does not actively pursue CCS at present. However, the outlook for its coal expansion plans provide opportunities for carbon removal for Poland to reach the EU commitments.
CCS targets	✗	No specific targets have been set for the deployment of CCS in Poland.
Total CCS Potential (MtCO2) 2022-2050	591	The largest share of capturable CO2 is expected to be derived from the power & heat sector (natural gas-fired power plants and biomass-fired plants). Significant potential also assessed within the industry (mainly iron and steel, and cement).
Own storage capacity (Mt)	78,000[131]	77,000 Mt of storage in aquifers – however, estimates are debatable and vary widely; 1,000 Mt of storage in depleted oil & gas fields

[130] PEP2040 – Poland's energy policy until 2040

[131] Mineral and Energy, Economy Research Institute of Polish Academy Sciences, "CO2 storage capacity of deep aquifers and hydrocarbon fields in Poland – EU GeoCapacity project results"

Own storage potential/support	TBD	CO2 storage is banned in Poland until 2024 (except for offshore demonstration projects). This could indicate that the country has no particular interest in storage at present. However, CCS is expected to become a highly relevant measure to offset emissions from the continued use of natural gas. Given that CO2 export can be more expensive than domestic storage, Poland is therefore expected to explore its own storage options (especially if the EU funding will be available)
Potential for DK storage	**MEDIUM**	Poland's domestic storage capacity can cover all upcoming CCS activity needs until 2050. However, only some of the upcoming CCS activity is expected to be covered by domestic storage capacity.

4.2.7.2 CCS national targets and policies Poland

Poland is aiming to reduce CO2 emissions by 85-90% from 1990 levels by 2050. However, the climate ministry presented an update of the country's 2040 energy roadmap at the end of 2020, where the country formally endorses the EU 2050 climate neutrality goal. Poland does not actively pursue CCS at present as a means of decarbonisation and has not set targets for CCS deployment. However, the Polish energy policy notes that there is institutional interest in CO2 capture projects, and the possibility of implementing them with the option to transport it outside Poland is not ruled out (e.g., in the North Sea region). Furthermore, in light of the planned expansion of Poland's coal industry, CCS can be expected to be necessary for Poland to reach its climate targets and EU commitments.

Currently, no national support system for CCS deployment is in place in Poland. Previously, through its R&D program "New Technologies for Energy Generation", Poland supported two CCS pilot facilities that tested varying capture approaches in Lagisza and Jaworno power plants from 2010-2015. Both projects were cancelled due to the high cost of the CCS technology as well as the influence of the social resistance coming from the rest of the EU of storing CO2 on geological formations. Further, a demo CO2 post-capture project was performed at Belchatow (on the new 858 MW lignite-fired unit), which was also abandoned at the stage of a CCS ready investment due to high cost and lack of sufficient (national) financial support[132]. However, the institutional interest in CCS remains, and the option of capturing CO2 and transporting it outside Poland is specifically noted in Poland's energy policy as a consideration.

Poland has basic legal and regulatory frameworks in place related to CCS. Poland has implemented the EU's CCS Directive by amending the Polish Geological and Mining Law. However, CO2 storage is banned in Poland until 2024, except for offshore demonstration projects. Under the amendments, Poland thus prohibits onshore storage and identifies only one storage site for commercial CO2 storage – in the Baltic Sea, which is located far from the biggest sources of CO2 emissions.[133]

Table 27: CCS national targets and policies in Poland

CCS NATIONAL TARGETS AND POLICIES		
Category	**Indicator**	**Comments**
Country CCS policy maturity/potential	◔	Poland does not actively pursue CCS at present.
National CO2 reduction targets	✓	• 2030: -21% in EU ETS sectors and -7% from 2005 levels (non-EU ETS) (-30% from 1990 levels)[134] • 2050: -85-90% from 1990 levels
National CCS targets	✗	Poland has no CCS targets.
CCS policies and legislations	–	Poland has basic regulatory and policy frameworks to enable CCS deployment in the country due to its EU membership. The energy policy of Poland mentions the so-called "CCS ready" requirements, and the decision to employ CCS will need to fulfil these requirements and be economically efficient.

[132] CCS – Polish Point of View, Basrec conference Warsawa

[133] Carbon neutral Baltic states: "Do we have CCUS among accepted options"

[134] PEP2040 – Poland's energy policy until 2040

CCS funding	✗	No national support systems in place.
CCS storage-related policies	✗	CO2 storage is banned in Poland until 2024, except for offshore demonstration projects. CO2 use for EOR and EGR and associated CO2 storage onshore and offshore are allowed.

4.2.7.3 CCS potential (capturable CO2 intended for storage) in Poland

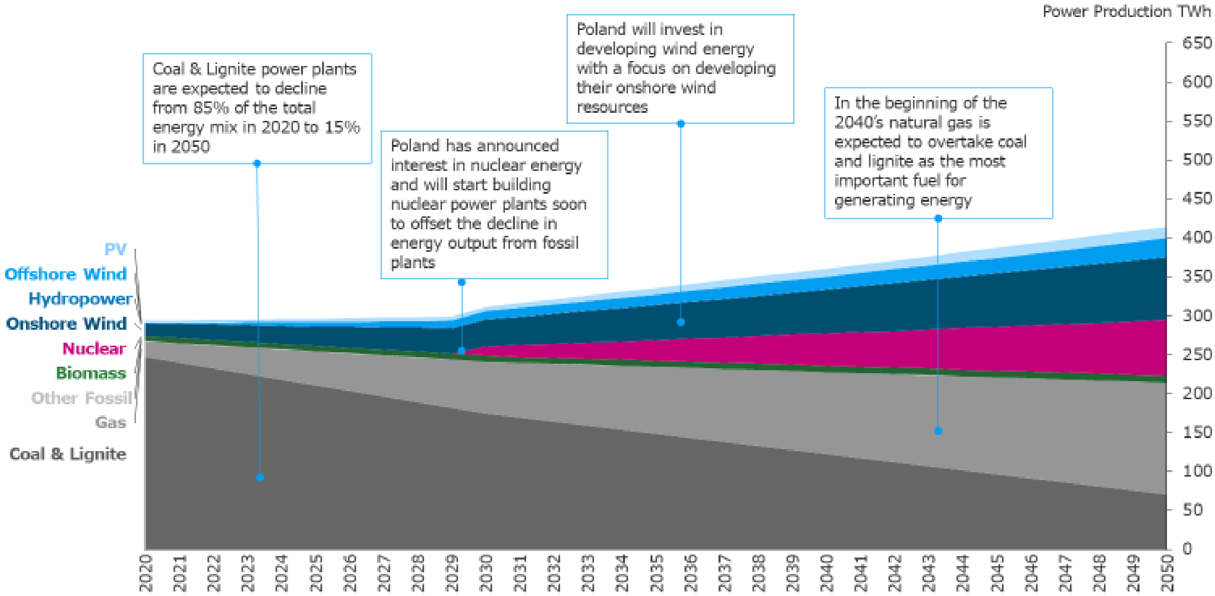
Total CO2 emissions from large sources[135] in Poland were ~167 MtCO2 in 2017, of which 121 MtCO2 were related to the power & heat sector, 22 MtCO2 to the industrial production and processing and the remaining 23 MtCO2 to other activities, including coal mining, landfill etc.

The overall significance of CCS within the power & heat sector in Poland is considered low, as renewables and nuclear energy are expected to lead the decarbonisation of the power sector. However, Poland's reliance on natural gas is expected to increase and be high at least until 2040. Furthermore, there are up to date no announced plans to completely discontinue the four newly build coal-driven power plants. Consequently, CCS is seen as necessary in order to abate the remaining CO2 emissions within the sector. Poland also has carbon sink potential due to large surface areas and large forest areas. However, forests are becoming mature, resulting in the decrease of the carbon sink potential. Other options in terms of agricultural fields/soil and wetlands are possible but would require significant investments. The total carbon sink is expected to be approximately 10 MtCO2e/y in 2050[136].

Poland's industry's decarbonization pathway will likely require the development of alternative fuels (hydrogen, biomass, and electricity), and CSS is seen as a last-resort option at scale. Decarbonisation of Poland's industry sector is also expected later on compared to the power & heat sector.

The calculated capturable quantity of CO2 is estimated at on average 19 MtCO2/y between 2022 and 2040 and 34 MtCO2/y between 2041 and 2050, with the largest share coming from the power & heat sector.

Figure 8: Poland's potential energy mix towards 2050



Source: Ramboll Analysis; Forum Energii, "Polish energy sector 2050"

[135] Plants with emissions exceeding 100,000 MtCO2/y

[136] Carbon-neutral Poland 2050: Turning a challenge into an opportunity, McKinsey & Company 2020

Table 28: CCS potential (intended for storage) in Poland

Sector	CO2 emissions 2017, MtCO2	Capturable quantity of CO2, MtCO2 (avg. MtCO2/y[137])		Comment
		2022-2040	2041-2050	
Power & Heat	**121.2**	**217** (**17**)	**310** (**31**)	• The overall significance of CCS within the power & heat sector in Poland is considered low, as renewables and nuclear energy are preferred options for decarbonisation of the power sector • However, switching power-generation technology from fossil fuels to renewable energy is expected to be a major challenge for Poland, and not all fossil sources will be decommissioned by 2050. Consequently, CCS is seen as a necessary measure in order to abate the remaining CO2 emissions within the sector • Although the overall decarbonisation of Poland's power & heat sector will be to a large degree driven by electrification, Poland has recently invested in a number of large power plants relevant for CCS (4 newer coal-fired plants and seven biomass-fired CHP plants) and five natural gas plants are planned to be delivered the mid-2020s. All of these plants are expected to operate towards 2050. The majority of the remaining installed coal capacity is older than 30 years and will most probably need to be decommissioned before 2050 • Total capturable CO2 volume from these plants is estimated at up to ~33 MtCO2/y
Industry	**22.4**	**32** (**3**)	**31** (**3**)	• CO2 emissions from the industrial sector were at 22 MtCO2 in 2017, primarily concentrated in iron and steel (7.1 MtCO2 in 2017) and cement (6.8 MtCO2 in 2017). Additional smaller amounts are assessed within refineries, non-ferrous metals and chemicals. • CCS would be an important measure to reduce emission within this sector, along with the development of alternative fuels (hydrogen, biomass, and electricity). However, CCS is still considered a last-resort option at scale in Poland. • Total capturable volume intended for storage is estimated at up to ~3 MtCO2/y, and the highest potential is assessed within the mineral processing/cement industry, where CCS is assessed to be the most effective way to significantly reduce emissions. Ramp-up of the CCS within the industrial sector is expected to be moderate, starting from 2030 and reach the full potential around 2040 • CCS is also considered highly relevant for reducing CO2 emissions within the iron and steel industry. Hydrogen is currently considered to be a preferred option to abate CO2 emissions within this industry. However, there are no provisions against the import and use of blue hydrogen. Blue hydrogen is therefore expected to be the transitional solution, creating the need for CCS • Some minor potentials are also assessed within the refining industry and chemical industry. However, in general, the chemical industry is prioritizing CCU over CCS
Other	**23.1**	**-**	**-**	• Other comprises coal mining, landfill and waste management. None of these are considered relevant for CCS in Poland

[137] Average CO2 capturable amount is calculated for the time period 2028-2040

4.2.7.4 CO2 storage potential in Poland

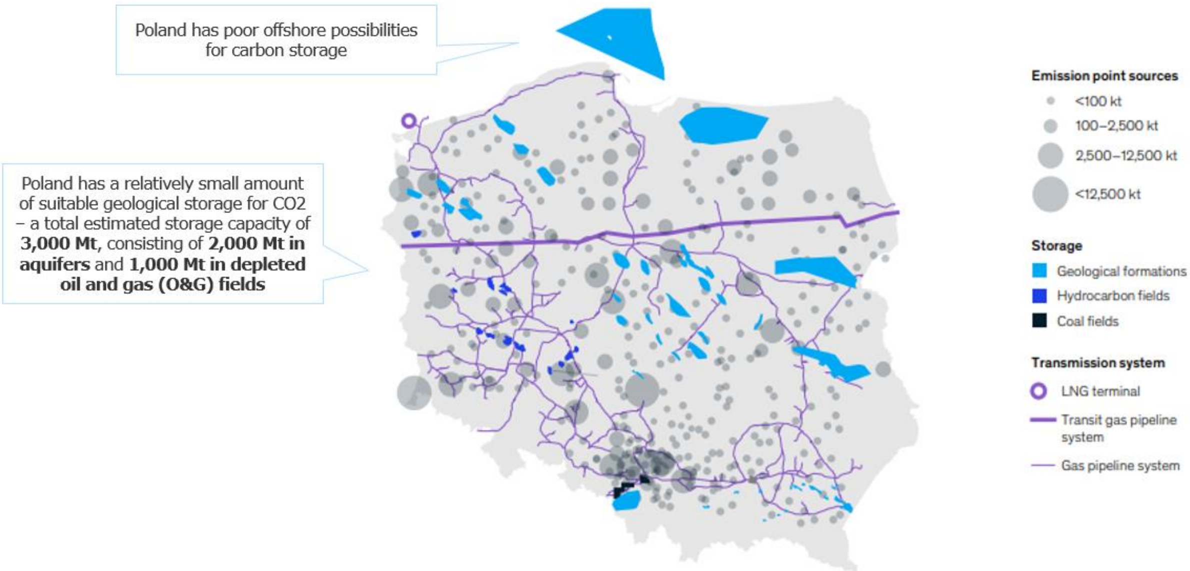
Poland has an estimated 78,000 Mt of storage capacity, of which the majority – 77,000 Mt – is situated in storage aquifers, and 1,000 Mt is situated in oil and gas fields[138]. Aquifer units are mostly located onshore, while oil and gas fields are located offshore and onshore. Only offshore storage can currently be developed; however, no development projects have been registered[139].

The storage capacity of oil and gas fields are mapped more accurately[140] and can theoretically cover Poland's CCS activity needs. The storage capacity could be too expensive to develop and operate due to the relatively small scale of the storage units and a lack of government will and incentives. The current situation suggests that Poland is not currently interested in developing storage. However, CCS is expected to become highly relevant as an emission offset measure for the continued use of natural gas. Given CO2 export can be more expensive than storage, Poland is expected to explore domestic storage opportunities, especially if EU finance is available[141].

The Polish public recognizes CCUS as an effective climate change technology[142]. However, currently little governmental support for the development of storage sites is provided, as described in section 4.2.7.2. This means that, while Poland's domestic storage capacity can cover all upcoming CCS activity needs until 2050, it is expected that only some of the upcoming CCS activity will be covered by domestic storage capacity.

The picture below details the location and relative size of the storage locations in Poland.

Figure 9: Overview of Carbon Storage in Poland



Source: McKinsey & Co., "Carbon-neutral Poland 2050: Turning a challenge into an opportunity"

4.2.8 Estonia

4.2.8.1 Summary of CCS potential in Estonia

Estonia's emissions from large stationary plants in 2017 were ~25 MtCO2, yet due to the closure of five oil shale plants from 2017-2020, emissions have been adjusted to ~12 MtCO2. Of the updated emissions, power and heat comprise 8.5 MtCO2, the industry comprises 2.6 MtCO2, whereas waste management comprises the remaining 1.4 MtCO2.

[138]Mineal and Energy, Economy Research Institute of Polish Academy of Sciences, "CO2 storage capacity of deep aquifers and hydrocarbon field in Poland- EU Geocapacity Results

[139] The Global CCS Institute, "Global Status of CCS 2020"

[140] Mineral and Energy, Economy Research Institute of Polish Academy of Sciences, "CO2 storage capacity of deep aquifers and hydrocarbon fields in Poland – EU GeoCapacity Project Results"

[141] Ramboll Expert

[142] Eurobarometer, "Public Awareness and Acceptance of CO2 capture and storage"

Estonia aims to become carbon neutral in 2050, but the country does not have any CCS specified targets. Nevertheless, the country's oil shale industry could suggest the potential for the implementation of CCS.

CCS potential in Estonia is estimated at 9.0 MtCO2 between 2022 and 2050, and on average 0.4 MtCO2/y between 2022 and 2040 and 0.5 MtCO2/y between 2041 and 2050, split fairly evenly between power & heat and industry. CCS potential is mainly related to power & heat (due to planned blue hydrogen production) and cement production (where CCS is the only option currently relevant for CO2 abatement). Within the industry sector, decarbonisation, cement is identified as a hard to abate emissions source. Thus CCS will likely play a role.

Storage potential in Estonia is low, as geological conditions are unfavourable for CO2 storage. National storage is therefore not viable, and CO2 would need to be exported to other countries.

Additionally, CO2 utilisation is also currently very limited and require high-quality CO2. A study from the University of Tallinn explored the options for using CCUS in Estonian oil shale-based energetics. Preliminary results showed that it is technologically possible but very costly[143]; thus, this strengthens further the case for CO2 export.

The relevance for storage in Denmark is deemed low, as the estimated volumes are too insignificant.

Below is an overview of the CCS potential in Estonia.

Table 29: Summary of CCS potential in Estonia

SUMMARY OF CCS POTENTIAL		
Category	**Indicator**	**Comments**
CO2 emissions 2017 (MtCO2) Plants >100 ktCO2	24.7	CO2 emissions from the largest point sources; mainly from heat and power industry powered oil shale, followed by the waste management and cement industry
Co2 reduction targets	✓	• 2030: -70% compared to 1990 (national target), and -13% compared to 2005 (non-EU ETS)[144] • 2050: climate neutral[145]
National CCS focus/Support	◔	Estonia's policies, regulations and climate plans do not actively pursue CCS development in the country today. However, as the country has recently committed to carbon neutrality and in an analysis which the Government commissioned, CCS/CCSU is mentioned as a prerequisite to reduce emissions to zero.
CCS targets	✗	No specific targets have been set for the deployment of CCS in Estonia.
Total CCS Potential (MtCO2) 2022-2050	6	Primary CCS potential comes from its oil shale production as well as the cement industry.
Own storage capacity (Mt)	0[146]	CO2 storage is not possible on Estonian territory as there are no suitable geological formations.
Own storage potential/support	○	Due to shallow setting, geological conditions in Estonia are unfavourable for CO2 storage. Therefore, Estonia would need to turn to the option of exporting CO2.
Potential for DK storage	Low	**Carbon storage outside the country seems likely, however, the estimated CCS volumes are deemed insignificant**

4.2.8.2 CCS national targets and policies Estonia

Estonia has committed to carbon neutrality by 2050. The country has no stated CCS targets. However, it would need to turn to CCS to reach climate targets if oil shale (local fossil fuel) based

[143] Interview with Tallinn University of Technology

[144] Estonia's 2030 National Energy and Climate Plan (NECP 2030)

[145] Stockholm Environment institute – "Reaching climate neutrality in Estonia"

[146] GEUS "EU GeoCapacity Assessing European Capacity for Geological Storage of Carbon Dioxide"

electricity and oil production continues. Government has a plan to stop producing oil shale[147] power by 2035[148]. To address this, Estonia, together with Latvia and Lithuania, will synchronise through Poland with a reliable and unified power system of continental Europe by 2025 to be able to increase the amount of renewable energy sources employed. However, the Estonian environment minister stated that the country could not drop oil shale until the power supply has been secured. Therefore, within the next decade, Estonia will need to decrease its dependency on oil shale, but the acceleration of this is uncertain, and thus, CO2 storage could be an additional mechanism for renewables to achieve its climate targets. Further, Estonia plans to produce blue hydrogen in the future. Producing Hydrogen with CCS could be one of the future options, and Bio-CCS may also help to reach carbon neutrality by 2050.

National financial support for research is targeted now for CO2 capture and use[149]. Based on the Estonian Government-commissioned study on a climate-neutrality scenario in 2050, total hard-to-abate emissions are estimated to be 2.1 MtCO2e (excluding Transport), with the energy sector contributing to close to zero emissions.

In 2019-2021, Tallinn University of Technology will carry out the project "Climate change mitigation through CCS and CCU technologies" to assess the suitability and work of different carbon capture technologies developed scenarios for the application of these technologies in the Estonian oil shale industry[150].

The absence of storage capacity in Estonia has meant that permanent storage of CO2 has been prohibited.

Estonia has ratified the London Protocol that allows CO2 export to other states for storage purposes.

Table 30: CCS national targets and policies in Estonia

CCS NATIONAL TARGETS AND POLICIES		
Category	**Indicator**	**Comments**
Country CCS policy maturity/potential	◔	CCS identified in the national climate strategy as potentially relevant, yet lack of supportive policy measures and regulatory restrictions create less favourable conditions for CCS.
National CO2 reduction targets	✓	• 2030: -70% compared to 1990 (national target), and -13% compared to 2005 (non-EU ETS)[151] • 2050: climate neutral[152]
National CCS targets	✗	Estonia does not actively pursue CCS and has no CCS facilities in operation/construction.
CCS policies and legislations	–	The NECP does not mention the strategic energy technology (SET) plan, even though Estonia is actively participating in three implementation working groups on photovoltaics, offshore wind and carbon capture utilisation and storage.[153] The applicable legislation mainly deals with the transportation and capture of CO2 rather than key aspects of CCS, such as monitoring and verification requirements, surface access and reclamation activities or closure regimes.[154]
CCS funding	✗	At the end of 2018, at the initiative of Norway, the Nordic Cooperation Group on Carbon Capture, Use and Storage (CCUS) and GHG Reduction (NGCCUS) were established, which could be a source of CCS funding. However, the Estonian development plan for research, development, innovation and entrepreneurship 2021-2035 is currently being developed, and thus more detailed funding and timeframes remain unclear.

[147] CO2 emission from oil shale combustion is significantly higher in comparison with other fossil fuels as energy sources. This is why CO2 emission per capita in Estonia is about two times higher than the average value in Europe.

[148] EER News, "Environment minister: Estonia cannot drop oil shale until supply is secured"

[149] Tallinn University of Technology – "Carbon neutral Baltic States: Do we have CCUS among accepted options?"

[150] Stockholm Environment Institute – "Raising Estonia's climate ambition analysis of possibilities"

[151] Estonia's 2030 National Energy and Climate Plan (NECP 2030)

[152] Stockholm Environment institute – "Reaching climate neutrality in Estonia"

[153] European Commission "Assessment of the final national energy and climate plan of Estonia"

[154] Global CCS Institute CO2RE database

CCS storage related policies	✕	The absence of storage capacity in Estonia has meant that the permanent storage of CO2 has been prohibited (with a limited exception for research purposes). Specifically, geological storage of carbon dioxide is prohibited in Estonia and under the continental shelf in accordance with the Earth's Crust Act, as well as within Estonia's maritime boundaries in accordance with the Water Act.[155]

4.2.8.3 CCS potential (capturable CO2 intended for storage) in Estonia

Total CO2 emissions from large stationary plants in Estonia were at ~25 MtCO2 in 2017. However, from 2017-2020, five oil shale plants have closed, and therefore the emissions have been adjusted to about ~12 MtCO2[156]. Of the updated amounts, power and heat comprise 8.5 MtCO2, the industry comprises 2.6 MtCO2, whereas waste management comprises the remaining 1.4 MtCO2.

The overall significance of CCS within the power & heat sector in Estonia is considered low, as renewables and nuclear energy are expected to lead the decarbonisation of the power sector. However, Estonia's reliance on oil shale mixed with biomass (maximum 20% of the mix) is expected to remain, although Estonia has introduced a target to phase out oil shale plants by 2035 due to the country's worry of energy supply security.

With regards to the industry, cement has been identified in Estonia's decarbonization pathway as a hard to abate emissions source, where CCS will likely play a role.[157]

The calculated capturable quantity of CO2 is estimated at on average 0.4 MtCO2/y between 2030 and 2040 and 0.5 MtCO2/y between 2041 and 2050, split fairly evenly between power & heat and industry.

[155] Global CCS Institute CO2RE database

[156] Tallinn University of Technology, "Carbon neutral Baltic states: do we have CCUS among accepted options?"

[157] Stockholm Environment Institute – "Raising Estonia's climate ambition analysis of possibilities"

Table 31: CCS potential (intended for storage) in Estonia

Sector	CO2 emissions 2017, MtCO2	Capturable quantity of CO2, MtCO2 (avg. MtCO2/y[158])		Comment
		2022-2040	2041-2050	
Power & Heat	**8.5**	**1.2** (0.1)	**0.5** (0.05)	• The overall significance of CCS within the Estonia power & heat sector is low due to the Government's focus on renewable power generation and nuclear. However, Estonia has expressed the need for energy supply security through domestic measures after having rapidly closed five oil shale production plants in recent years; thus, this might pose a deployment of CCS at the currently existing fossil fuel-driven power plants starting from 2030. Nevertheless, the Government has announced a target of phasing out all oil shale plants by 2035. Therefore it is expected that 50% of currently operating plants will be closed by 2035. From 2035-2050 it is estimated that 50% of energy will be produced by renewable energy and nuclear, whereas the other 50% will be produced from other fuels mixed with biomass (the maximum share of biomass mix is 20%). Based on these trends and assumptions, CCS is assumed to be utilised for 20% of the emissions from the early 2030s • The capturable volume of CO2 intended for storage within the segment is estimated at up to 0.2 MtCO2/y (peak between 2030 and 2040)
Industry	**2.6**	**1.4** (0.1)	**3.3** (0.2)	• Estonia has a small industrial sector with an emission of 2.6 MtCO2 in 2017, including cement production and other wood processing. The emissions relevant for CCS come solely from cement (0.6 MtCO2), which are hard to abate emissions in 2050 • CCU is a competitor to CCS and is preferred compared to CCS. Therefore CCS of the cement emissions are estimated from 30-40% between early 2030 to 2050 • The capturable volume of CO2 intended for storage within the segment is estimated at up to 0.5 MtCO2/y in 2050
Other	**1.4**	**-**	**-**	• No other significant potential areas have been assessed

4.2.8.4 CO2 storage potential in Estonia

Carbon storage in Estonia is unfavourable due to unsuitable geological conditions[159]. Any domestic storage of Carbon is prohibited by law, as described in section 4.2.8.2.

Estonian attitude towards CCS technology is favourable in the shape of national financial support for research projects while also allowing the export of carbon for storage[160]. However, Estonia does not currently have CCS facilities in operation or construction[161].

As a result, Estonia does not have the storage capacity to cover upcoming CCS activity and will be looking to export captured carbon.

[158] Average CO2 capturable amount is calculated for the time period 2030-2040

[159] Institute of Geology, Tallinn University of Technology, "Possibilities for geological storage and mineral trapping of industrial CO2 emissions in the Baltic Sea"

[160] Tallinn University of Technology, "Carbon Neutral Baltic States: Do we have CCUS among accepted options"

[161] The Global CCS Institute, "Global Status of CCS 2020"

4.2.9 Lithuania

4.2.9.1 Summary of CCS potential in Lithuania

Lithuania's emissions from large stationary plants in 2017 were ~5 MtCO2, of which only 0.1 MtCO2 were related to the power & heat sector. Most emissions relate to waste-to-energy plants and the remaining industry, including oil & gas refineries, chemical production and cement production.

Lithuania is aiming to become carbon neutral by 2050. Lithuania's strong focus on renewable energy is reflected in the 45% renewable energy share in final energy consumption in 2030. While the Lithuanian government states that CCSU technologies are required to reduce the cost of renewable energy, no specified CCS targets are mentioned in the Government's National energy and climate strategies.

CCS potential in Lithuania is estimated at 7.4 MtCO2 between 2022 and 2050 and on average 0.4 MtCO2/y between 2022 and 2040 and 0.3 MtCO2/y between 2040 and 2050. In general, very small potential is assessed for CCS by 2050, as oil and gas have been phased out, and other alternatives such as CCU are prioritized in the rest of the industry.

Storage potential in Lithuania is estimated to be 2.2 Mt. However, both onshore and offshore CO2 storage was recently banned in Lithuania (July 2020).

The relevance for storage in Denmark is deemed low, as the estimated volumes are too insignificant.

Below is an overview of the CCS potential in Lithuania.

Table 32: Summary of CCS potential in Lithuania

SUMMARY OF CCS POTENTIAL		
Category	**Indicator**	**Comments**
CO2 emissions 2017 (MtCO2) Plants >100 ktCO2	5.19	CO2 emissions from largest point sources; mainly chemicals production industry focusing on the production of fertiliser and ammonia, followed by the mineral oil and gas industries
Co2 reduction targets	✓	• 2030: -43% from 2005 levels (EU ETS) and -9% from 2005 levels (non-EU ETS)[162] • 2040: -70% from 1990 levels (all sectors) 2050: Carbon neutral: -80% from 1990 levels (all sectors) and -20% absorbed by LULUCF carbon sink
National CCS focus/Support	◔	Lithuania's policies, regulations and climate plans do not actively pursue CCS development in the country today. However, the country has recently committed to carbon neutrality, and CCS is mentioned as potentially relevant to achieve climate neutrality.
CCS targets	✗	No specific targets have been set for the deployment of CCS in Lithuania.
Total CCS Potential (MtCO2) 2030-2050	7	The potential is deemed from oil and gas refineries primarily, who are the main advocates for CCS, however, will be phased out by 2045.
Own storage capacity (Mt)	2,286[163]	2,280 Mt of storage in aquifers and 6 Mt of storage in oil and gas fields
Own storage potential/support	◔	Lithuania recently banned CO2 injection, and thus, CO2 storage is not permitted onshore or offshore[164].
Potential for DK storage	**Low**	**Carbon storage outside the country seems likely, however, the estimated CCS volumes are deemed insignificant**

[162] Lithuania's Integrated National Energy and Climate Plan (NECP 2030)

[163] GEUS "Assessment of CO2 Storage Potential in Europe"

[164] Lithuanian Parliament, LRT news

4.2.9.2 CCS national targets and policies Lithuania

Lithuania aims to become carbon neutral by 2050, allowing 20% of CO2 reductions to be absorbed by the LULUCF carbon sink. While the Lithuanian government states that CCSU technologies are required to reduce the cost of renewable energy and that further developing CCUS technologies and analysing their applications in Lithuania is necessary, **no specified CCS targets** have been set in Lithuania. Lithuania's strong focus on renewable energy is reflected in the 45% renewable energy share in final energy consumption in 2030.

Latvia does not have national support systems in place for CCS funding. According to the country's NECP, 2% in its SET-plan will be allocated to CCS of the share of total R&I investments from 2021-2027 in the field of energy[165]. However, despite these developments, CCS is not considered a priority in Latvia today.

Lithuania's legal and regulatory framework related to CCS activities has been developed to address multiple elements of the project lifecycle. The framework transposes the requirements of the EU storage Directive into national law. The licensing regime adopted is similar to other models governing the country's oil, gas, and mining operations. While several elements of the resulting framework are well characterised, some aspects of the CCS project lifecycle have yet to be fully addressed. In addition, Lithuania has recently banned CO2 injections, thereby permitting neither onshore nor offshore storage[166].

Table 33: CCS national targets and policies in Lithuania

CCS NATIONAL TARGETS AND POLICIES		
Category	**Indicator**	**Comments**
Country CCS policy maturity/potential	◔	CCS identified in the national climate strategy as potentially relevant, yet lack of supportive policy measures and regulatory restrictions create less favourable conditions for CCS.
National CO2 reduction targets	✓	• 2030: -43% from 2005 levels (EU ETS) and -9% from 2005 levels (non-EU ETS)[167] • 2040: -70% from 1990 levels (all sectors) • 2050: Carbon neutral: -80% from 1990 levels (all sectors) and -20% absorbed by LULUCF carbon sink
National CCS targets	✗	The country has no CCS targets. However, the National energy and climate action plan from 2021-2030 outlines that technology will play a central role in achieving its energy policy goals, one such technology mentioned is CCS.[168]
CCS policies and legislations	—	The country has developed a legal and regulatory model for CCS activities, which addresses multiple elements of the project lifecycle and transposes the requirements of the EU storage Directive into national law.
CCS funding	✗	Latvia will allocate 2% in its SET-plan priorities to CCS of the share of total R&I investments from 2021-2027 in the field of energy[169]. However, CCS is not considered a priority.
CCS storage-related policies	✗	Lithuania recently banned CO2 injection, and thus, CO2 storage is not permitted onshore or offshore[170].

[165] Latvia's national energy and climate plan, 2021-2030

[166] Lithuanian Parliament, LRT news

[167] Lithuania's Integrated National Energy and Climate Plan (NECP 2030)

[168] National energy and climate action plan of the republic of Lithuania for 2021-2030

[169] Latvia's national energy and climate plan, 2021-2030

[170] Lithuanian Parliament, LRT news

4.2.9.3 CCS potential (capturable CO2 intended for storage) in Lithuania

Total CO2 emissions from large stationary plants in Lithuania were at ~5 MtCO2 in 2017. Only 0.1 MtCO2 were related to the power & heat sector; From waste-to-energy plants, and the rest from industry, including oil & gas refineries, chemical production and cement production.

Lithuania is mainly focused on renewable energy, so the emissions are already to date minimal in the power and heat sector.

Lithuania's climate plan notes that the country will make maximum use of natural carbon sinks and prefers CCU above CCS; only environmentally safe CCS technologies will be used to ensure a 100% reduction in the industry segment[171]. There is reportedly one oil company that is advocating the use of CCS[172]. Further, the fossil fuel industry will be fully abandoned by 2045 and will be replaced by green hydrogen.

The calculated capturable quantity of CO2 is estimated at on average 0.4 MtCO2/y between 2022 and 2040 and 0.3 MtCO2/y between 2041 and 2050.

Table 34: CCS potential (intended for storage) in Lithuania

Sector	CO2 emissions 2017, MtCO2	Capturable quantity of CO2, MtCO2 (avg. MtCO2/y[173])		Comment
		2022-2040	2041-2050	
Power & Heat	**0.1**	**0.2** (**0.02**)	**0.2** (**0.02**)	• The overall significance of CCS within the Lithuanian power & heat sector is insignificant due to the lack of emissions in this sector as renewables have been employed at large-scale already • The capturable volume of CO2 within the segment is estimated below ~0.1 MtCO2/y in 2050
Industry	**5.1**	**4.4** (**0.4**)	**2.6** (**0.3**)	• The significance of CCS in the industry is low since other carbon removal means are prioritised, such as CCU • CCS will be mainly relevant for the oil & gas industry, which only comprise 1.7 MtCO2 in 2017 since CCU is preferred for the other industry sectors (cement and chemical production) • CCS is estimated to rise up to comprise about 20% of emissions reduction for industry from 2035 to 2045 • Since the fossil fuel industry will be phased out by 2045, the CCS potential from the oil & gas sector is removed, and Ramboll estimates the capture potential to be only 10% of emissions • The capturable volume of CO2 intended for storage within the segment is estimated to peak from 2035-2045 at 0.6 MtCO2/y and will decrease with the closure of oil & gas refineries (largest advocate of CCS) by 2045 to below 0.1 MtCO2/y towards 2050
Other	-	-	-	• No other significant potential areas have been assessed

[171] Latvia's national energy and climate plan, 2021-2030

[172] Expert interview with Baltics representative from Tallinn University of Technology

[173] Average CO2 capturable amount is calculated for the time period 2030-2040

4.2.9.4 CO2 storage potential in Lithuania

Lithuania's total carbon storage capacity is 2,280 Mt, situated almost exclusively in aquifer storage units with 5.8 Mt of storage capacity located in oil and gas fields[174]. However, the aquifer storage units are located close to the surface and have not been tested for any leakages, which is a long and expensive process.

As described in section 4.2.9.2, any carbon storage is prohibited in Lithuania, but that could change in the short term as new politicians are elected. The attitude towards CCS technologies in Lithuania is considered favourable[175] as several carbon capture facilities have been planned with the intention of exporting the captured carbon[176].

As a result, Lithuania has adequate domestic storage to cover upcoming CCS activities but does not plan to develop the storage sites. This means that any carbon captured from upcoming CCS activities will have to be exported for storage.

4.2.10 Latvia

4.2.10.1 Summary of CCS potential in Latvia

Latvia's emissions from large stationary plants in 2017 were ~1 MtCO2. Thermal power and heat comprise the total amount of these emissions. Latvia (and Lithuania) has significantly lower emissions than Estonia due to the utilisation of other main energy sources (nuclear and hydro-energy) than oil shale.

Latvia is aiming to become carbon neutral in 2050. As energy and transport sectors comprise ~64% of total GHG emissions in 2017, these sectors are expected to play a significant role in achieving the goal. Latvia's carbon neutrality strategy states that CCS could be relevant for industrial sectors, yet not in the significant energy and transport sectors. The potential for CCS in Latvia is low as the country has no industrial plants >100 ktCO2.

Latvia's CCS potential is estimated at 2.2 MtCO2 between 2022 and 2050, and on average 0.1 MtCO2/y between 2022 and 2040 and 0.1 MtCO2/y between 2040 and 2050, and the potential is mainly related to the power & heat sector. Latvia does not have industrial plants above 100 ktCO2 (where CCS could be applied), and therefore, the potential for CCS in Latvia is considered low.

Storage potential in Latvia is estimated to be 3,400 Mt in aquifers. The relevance for storage in Denmark is deemed low, as the estimated volumes are so insignificant.

Below is an overview of the CCS potential in Latvia.

Table 35: Summary of CCS potential in Latvia

SUMMARY OF CCS POTENTIAL		
Category	**Indicator**	**Comments**
CO2 emissions 2017 (MtCO2) Plants >100 ktCO2	1.0	CO2 emissions from the largest point sources; mainly from the power and heat generation industry
Co2 reduction targets	✓	• 2030: -65% from 1990 (national target) and -6% from 2005 (non-EU ETS)[177] 2050: Carbon neutral
National CCS focus/Support	◔	Latvia's policies, regulations and climate plans do not actively pursue CCS development in the country today. However, the country has recently committed to carbon neutrality, and CCS is mentioned as potentially relevant to achieve climate neutrality.
CCS targets	✗	No specific targets have been set for the deployment of CCS in Latvia.

[174] GEUS, "Assessment of CO2 storage potential in Europe"
[175] IOGP, "the potential for CCS and CCU in Europe"
[176] Tallinn University of Technology, "Carbon Neutral Baltic States: Do we have CCUS among accepted options?"
[177] Latvia's Integrated National Energy and Climate Plan (NECP 2030)

Total CCS Potential (MtCO2) 2022-2050	2	Mainly related to the power & heat sector
Own storage capacity (Mt)	3,400[178]	3,400 Mt of storage in aquifers
Own storage potential/support	◔	Domestic CO2 storage is not currently permitted in Latvia and as no experiments have been conducted to ensure geological suitability for carbon storage, developing these sites would be difficult and could take several years[179]
Potential for DK storage	**Low**	**Carbon storage outside the country seems likely, however, the estimated CCS volumes are deemed insignificant**

4.2.10.2 CCS national targets and policies Latvia

Latvia aims to become carbon neutral by 2050 but does not actively pursue CCS as a means to achieve this climate target and currently has no CCS facilities in planning/construction. Thus, **no specific targets related to CCS** have been set either. However, Latvia's carbon neutrality strategy states that CCS could be relevant for energy and industrial sectors[180], indicating that the policy support for CCS is slightly maturing.

Latvia has not previously provided funding or support to CCS research or projects. However, the NECP indicates that Latvia will spend 2% of investments in total R&I investments in the field of energy on CCS between 2021-2027[181]. However, the funds allocated to energy research are not described, making it difficult to assess the degree to which the 2% to CCS is sufficient.

Latvia's regulatory framework related to CCS has transposed the requirements of the EU storage Directive into national law. However, it has also prohibited CO2 storage in the country. Latvia's legal and regulatory framework considers some parts of the CCS project cycle, including the operator's responsibilities, carbon dioxide purity criteria and dispute resolution procedures, yet key aspects of the CCS process such as storage and closure are not addressed due to the prohibition and storage of CO2[182].

Table 36: CCS national targets and policies in Latvia

CCS NATIONAL TARGETS AND POLICIES		
Category	**Indicator**	**Comments**
Country CCS policy maturity/potential	◔	CCS identified in the national climate strategy as potentially relevant, yet lack of supportive policy measures and regulatory restrictions create less favourable conditions for CCS.
National CO2 reduction targets	✓	• 2030: -65% from 1990 (national target) and -6% from 2005 (non-EU ETS)[183] • 2050: Carbon neutral
National CCS targets	✗	No specific targets have been set for the deployment of CCS in Latvia.
CCS policies and legislations	✗	Latvia's regulatory framework has transposed the EU storage Directive into national law. However, the framework prohibits CO2 storage in the country.
CCS funding	✗	No national support system for the deployment of CCS in place, yet Latvia's NECP indicates that funds will be allocated to R&I in the field of energy on CCS between 2021-2027[184], although it is unclear if the funds will suffice for the deployment of CCS.
CCS storage-related policies	✗	According to Section 82 of the Law On Pollution, storage of carbon dioxide in geological formations and the water column is prohibited in the territory of Latvia, the exclusive economic zone and continental shelf thereof.[185]

[178] GEUS "Assessment of CO2 Storage Potential in Europe"
[179] Ramboll Expert
[180] Strategy of Latvia for the Achievement of Climate Neutrality by 2050
[181] Latvia's Integrated National Energy and Climate Plan (NECP 2030)
[182] Global CCS Institute CO2RE database
[183] Latvia's Integrated National Energy and Climate Plan (NECP 2030)
[184] Latvia's Integrated National Energy and Climate Plan (NECP 2030)
[185] Ecolex - Latvia, Law on pollution

4.2.10.3 CCS potential (capturable CO2 intended for storage) in Latvia

Total CO2 emissions from large stationary plants in Latvia were ~1 MtCO2 in 2017, of which all amounts come from thermal power and heat.

The overall significance of CCS within the thermal power and heat is considered low, as renewables are expected to lead the decarbonisation of the power sector. However, in its strategy towards carbon neutrality in 2050, Latvia mentions with regards to the energy sector that the assessment of the introduction of new technologies in relation to carbon capture and storage should be taken into consideration.

The calculated capturable quantity of CO2 is estimated at on average 0.1 MtCO2/y between 2022 and 2040 and 0.1 MtCO2/y between 2040 and 2050.

Table 37: CCS potential (intended for storage) in Latvia

Sector	CO2 emissions 2017, MtCO2	Capturable quantity of CO2, MtCO2 (avg. MtCO2/y[186])		Comment
		2022-2040	2041-2050	
Power & Heat	**1**	**1.2** **(0.1)**	**1.0** **(0.1)**	• The potential for the power and heat sector is low since the Latvian Government has plans to reduce its emissions with renewable energy. However, in its strategy towards carbon neutrality in 2050, Latvia mentions with regards to the energy sector that the assessment of the introduction of new technologies in relation to carbon capture and storage should be taken into consideration[187] • Ramboll assesses that CCS could capture up to 20% of power and heat emissions towards 2050 since there are potential competing alternatives that could be preferred, such as CCU[188] • The CCS potential is about 0.1 MtCO2/y in 2050
Industry	**-**	**-**	**-**	They have mentioned plans to employ CCUS within the industry sector, however, their industry sectors do not have large stationary plants (above 100 ktCO2/y), which is why CCS potential is not considered.
Other	**-**	**-**	**-**	• No other significant potential areas have been assessed

[186] Average CO2 capturable amount is calculated for the time period 2030-2040

[187] Strategy of Latvia for the Achievement of Climate Neutrality by 2050

[188] Interview with CCUS expert in Baltics

4.2.10.4 CO2 storage potential in Latvia

Latvia has a carbon storage capacity of 3,400 Mt, of which the majority, 3,000 Mt, is situated in aquifers, and 400 Mt is situated in oil and gas fields[189]. Some capacity in the oil and gas fields is currently being used for the storage of natural gas[190]. However, experiments testing the geological suitability for carbon storage have not been initiated and could take years to complete adding to the cost of developing domestic storage capacity[191].

As described in section 4.2.10.2, any storage of carbon is currently prohibited domestically in Latvia. However, this could change in the short term, as governmental opinion changes following election cycles. Latvian attitude towards CCS is regarded as neutral[192] due to small CCS incentives and lack of recognition of CCS in the national 2050 climate strategy[193]. Moreover, Latvia has not yet allowed the export of carbon for storage but has been urged to by experts[194].

As a result, Latvia does not have the carbon storage capacity to cover all upcoming CCS activity.

[189] GEUS, "Assessment of CO2 storage potential in Europe"
[190] Ramboll/DEA, "Cata
[191] Ramboll Expert
[192] IOGP, "The potential for CCS and CCU in Europe"
[193] INFORSE-Europe, "Sustainable Energy Strategy for Latvia's: Vision 2050"
[194] Tallinn University of Technology, "Carbon Neutral Baltic States: Do we have CCUS among accepted options?"

4.3 ASSUMPTIONS UNDERLYING ESTIMATION OF CAPTURABLE CO2

Data basis for CO2-emissions

The analysis presented in this report is based on emissions data retrieved from the E-PRTR emissions data from the year 2017. The year 2017 was chosen as it comprises the most complete data set, where all countries had had the opportunity to re-report and confirm emission numbers. Moreover, the E-PRTR database includes emissions from biogenic sources, which are relevant from a CCS perspective.

Due to the incompleteness of the E-PRTR emissions data set in years after 2017, it is not possible to compare emissions from that database to identify trends or outliers that can impact the estimates presented in the report. As a result, emissions data from the EU-ETS database from 2017 and 2019 was used. Specifically, the industrial 'Combustion of fuels' emissions was used. This covers the emissions released as a direct result of the combustion of fuels used for heating in plants emitting more than 100 ktCO2/year. These emissions were compared to identify trends and outliers.

Box 1 - A note on emissions comparison

Emissions compared below are based on values from the EU-ETS emissions database from the years 2017 and 2019 respectively. The emissions are the confirmed unadjusted values. have been used as a tool to identify potential countries with severe reductions in emissions and thus potentially need to have emissions values adjusted to reflect the countries' current emission-level. The E-PRTR database does not fully cover both 2017 and 2019 for all countries that have been analyzed. As a result, the EU-ETS emissions database has been used instead. The datasets included in this database have all been confirmed and the database covers all countries that have been analyzed in this report.

Table 38: EU-ETS emissions comparison

EU-ETS 'Combustion of Fuels' emissions comparison										
	FI	SE	NO	DE	UK	NL	PL	EE	LT	LV
EU-ETS emissions, 2017 [MtCO2]	12.4	8.1	14.2	313.4	98.1	61.3	162.8	12.5	0.9	1.3
EU-ETS emissions, 2019 [MtCO2]	11.3	7.2	13.7	245.4	81.5	53.9	144.8	6.2	0.6	1.6
%-change	-9%	-11%	-3.5%	-22%	-17%	-12%	-11%	-50%	-33%	23%
Comments				The decline in emissions between 2017 and 2019 in Germany was caused by the decrease in coal usage at power plants[195].	The UK experienced a rapid decline in CO2 emissions between 2017 and 2019 as the heat & power sector cut emissions by 60%[196].			Estonia has phased out several plants between 2017 and 2019[197].	Lithuania decreased emissions by 1/3 between 2017 and 2019 due to large decrease in the use of natural gas and by the heat & power sector[198].	Latvia has seen an increase in emissions due to the national energy strategy focusing on independent energy supply[199].

[195] Clean Energy Wire, "Germany's CO2 emissions set to fall markedly in 2019 as energy use declines"

[196] IEA Emissions Database

[197] Interview with Tallinn University CCS professor

[198] IEA Emissions Database

[199] National Energy and Climate Plan of Latvia

The general trend among all countries included in the analysis is a decline in emissions which is expected due to the global focus on reducing GHG emissions. Events or actions causing substantial drops in emissions have all been addressed in our calculated estimates.

In Germany, 70% of the emissions are caused by the heat & power sector, which is currently going through a transition away from coal and oil towards natural gas and zero-emission technologies. This has been accounted for in the estimates for CCS potential as CCS on coal and oil power plants have been assumed to be zero due to the phase-out of coal and oil in Germany by as early as 2030 and 2038 at the latest. The United Kingdom, Poland, Estonia, and Lithuania all have power sectors going through similar transitions, which have also had certain power generation technologies excluded due to expected decommission before CCS reaches maturity. This is done because retrofitting CCS technology to plants scheduled for decommissioning would be ineffective as only insignificant amounts of CO2 emissions would end up being captured by the CCS system. Fitting CCS technology to a newer plant which is expected to run for a long time, would yield larger amounts of captured carbon and make more sense as an investment as a result.

Latvia is the only country that has had its emissions increased. This is due to the country's national energy strategy, which is currently focusing on achieving a larger share of energy independence. Currently, Latvia imports approximately 70% of the country's electricity mostly from Sweden and any domestic production of electricity would as a result increase the emissions of Latvia. Moreover, Latvia's emissions are insignificant compared to, e.g. Germany and Poland and has, as a result, had a low impact on the overall CCS potential estimates.

Technical assumptions for CCS potential

Estimation of CCS potential within each country is based on CO2 emissions from large sources, multiplied by technically capturable share (country-based adjustments have been applied where necessary based on Ramboll's technical insights), and again multiplied by the expected share of CO2 that will be stored (estimated CCS share).

In the definition of the technical capture potential, this report applied some general assumptions for technically capturable volumes connected with the power & heat plants and plants within the energy-intensive industries in Europe.

Table 39: Assumptions underlying technically capturable volume (technical capture potential) across the analysed countries

Sector	Industry	Significance of CCS	CCS application[200]	Technical capture potential % [201]
Power and heat generation	Power and heat plants, including fossil, biomass-fired plants etc.	In general, LOW for fossil-fired plants, as the focus is typically on renewable power generation. However, for some European countries currently heavily relying on coal power generation, CCS on coal power plants could be an attractive option. MEDIUM/HIGH for biomass plants (incl. incineration plants) due to interest for BECCS that can provide	CCS can be used in thermal power and heat plants regardless of the fuel used during combustion is fossil or renewable. The technology can be retrofitted to existing plants or applied to newly constructed plants by collecting and 'cleaning' the flue gasses from the stacks.	Up to ~90%

[200] Based on Ramboll's technical insights and external research (mainly *The role of Carbon Capture and Storage in a Carbon Neutral Europe, Carbon Limits, 2020)*

[201] Share of volumes that are technically feasible to capture; Input based on Ramboll's technical insights and external research (mainly *The role of Carbon Capture and Storage in a Carbon Neutral Europe, Carbon Limits, 2020)*

		negative emissions compensating some industry and agricultural emissions hard to abate.		
Energy-intensive industry	Iron and steel (incl. other ferrous metals)	MEDIUM; Both CCS and hydrogen can be applied. Hydrogen replacing fossil fuels is expected to be the preferred option. However, if hydrogen from natural gas (blue hydrogen) is applied, then CCS is key.	CCS can be applied to current blast furnaces in the steel-making process responsible for most of the CO2 emissions in the iron and steel industry, enabling up to 50% reduction of emissions. Alternatively, direct smelting technology could be used to concentrate CO2 generation further, enabling higher amounts of emissions reduction.	Up to ~60%
	Refineries	HIGH as emissions from refining and mineral oil and gas are hard to abate.	CO2 production from refineries is spread over multiple stacks with varying CO2 emission amounts making it infeasible to capture CO2 from all sources.	Up to ~50%
	Mineral production (mainly cement, but also glass ceramics etc.)	HIGH, CCS is key in the cement sector as there are no other ways to reduce the process emissions significantly. While the use of biomass instead of fossil fuels can reduce some emissions, BECCS would still be relevant to provide negative emissions).	In the cement sector, 60-65% of CO2 is generated during the heating process due to the combustion of fuels providing heat and because of a reaction within the cement during the heating process.	Up to ~50%
	Chemicals	MEDIUM; Mostly transitional solution as renewable energy sources can be applied; In general, the chemical industry is prioritising CCU over CCS.	CCS can be applied to process emissions as well as emissions from fuel combustion. Application varies due to high diversity of the sector. Ammonia and blue hydrogen production produce a relatively pure CO2 stream, potentially allowing for very high capture rates.	Up to ~50%
	Pulp & paper	HIGH; Pulp and paper industry in most cases utilise production residuals/biomass as energy input in processing; BECCS here would be key here to compensate for emissions from other industries where they are harder to abate. Pulp and paper plants are often located close to coastline and rivers (as they need water in production), and this makes it potentially easier to transport CO2	During the chemical pulping process, woodchips are cooked by burning by-products from the paper-making process. Installing CCS technology can be applied to capture carbon from flue gasses.	Up to ~90%

Estimated CCS share reflects what is actually expected for CCS given alternatives (CCU, renewable energy, heat pumps etc), and is based on high-level qualitative and country-specific analysis (interviews and available research).

Box 2 – Estimated CCS share

Note that table below presents the maximum estimated capturable share, i.e. peak share expected after years of gradual ramp-up.

Overview of assumptions for CO2 emissions from large sources, technical potential and estimated CCS share per country are presented in the table below. See appendix for more information on estimated CCS share.

Table 40: Overview of assumptions for CO2 emissions, technical potential, and estimated CCS share (peak estimates) potential per country

Industry	Sub-industry	FI			SE			NO			DE			UK		
		CO2 emissions 2017	Tech. potential	Est. CCS share	CO2 emissions 2017	Tech. potential	Est. CCS share	CO2 emissions 2017	Tech. potential	Est. CCS share	CO2 emissions 2017	Tech. potential	Est. CCS share	CO2 emissions 2017	Tech. potential	Est. CCS share
Power and heat	Thermal power and heat generation	16,9	90%	N/A	11,7	90%	N/A	14,2	90%	50%	263,8	90%	5%	99,7	90%	10%
	WtE plants	0,2	90%	90%	4,8	90%	90%	0,0	90%	N/A	16,4	90%	50%	9,9	90%	80%
Industrial plants	Steel & iron production/ferrous metals	1,5	60%	60%	4,1	60%	0%	2,5	60%	50%	28,6	60%	20%	6,7	60%	50%
	Non-ferrous metals (aluminium, copper and zinc etc)	0,0	N/A	N/A	0,7	N/A	N/A	2,7	N/A	N/A	1,7	N/A	N/A	0,0	N/A	N/A
	Mineral oil and gas refineries	3,1	50%	50%	2,7	50%	50%	2,6	50%	75%	21,1	50%	30%	10,8	50%	25%
	Chemicals production	0,7	50%	50%	1,0	50%	25%	1,5	50%	25%	24,6	50%	30%	4,8	50%	25%
	Chemicals production (fertiliser/ammonia production)	0,0	50%	N/A	0,0	50%	N/A	0,0	50%	N/A	0,0	50%	0%	0,6	50%	25%
	Pulp & paper	20,3	80%	80%	22,8	80%	80%	0,2	80%	50%	0,0	80%	N/A	0,0	80%	N/A
	Mineral production (cement)	1,3	90%	90%	2,8	90%	90%	1,2	90%	90%	25,0	90%	50%	7,2	90%	90%
	Mineral production (lime, plaster, ceramics, glass etc)	0,0	90%	N/A	0,0	90%	N/A	0,5	90%	90%	0,9	90%	N/A	1,0	90%	90%
	Food processing	0,0	90%	N/A	0,0	90%	N/A	0,0	90%	N/A	0,8	90%	N/A	1,2	90%	50%
Other	Other	2,9	N/A	N/A	0,7	N/A	N/A	0,0	N/A	N/A	23,3	N/A	N/A	4,4	N/A	N/A
Total		**46,8**			**51,3**			**25,4**			**406,2**			**146,3**		

Industry	Sub-industry	NL			PL			EE			LT			LV		
		CO2 emissions 2017	Tech. potential	Est. CCS share	CO2 emissions 2017	Tech. potential	Est. CCS share	CO2 emissions 2017	Tech. potential	Est. CCS share	CO2 emissions 2017	Tech. potential	Est. CCS share	CO2 emissions 2017	Tech. potential	Est. CCS share
Power and heat	Thermal power and heat generation	55,7	90%	5%	121,2	90%	30%	7,9	90%	5%	0,0	90%	N/A	1,0	90%	20%
	WtE plants	8,9	90%	90%	0,0	90%	N/A	0,0	90%	N/A	0,1	90%	20%	0,0	90%	N/A
Industrial plants	Steel & iron production/ferrous metals	0,0	60%	N/A	7,1	60%	30%	0,0	60%	N/A	0,0	60%	N/A	0,0	60%	N/A
	Non-ferrous metals (aluminium, copper and zinc etc)	0,0	N/A	N/A	1,2	N/A	N/A	0,0	N/A	N/A	0,0	N/A	N/A	0,0	N/A	N/A
	Mineral oil and gas refineries	10,6	50%	90%	1,7	50%	50%	0,0	50%	N/A	1,7	50%	0%	0,0	50%	N/A
	Chemicals production	16,9	50%	75%	1,0	50%	10%	0,0	50%	N/A	0,0	50%	N/A	0,0	50%	N/A
	Chemicals production (fertiliser/ammonia production)	0,0	50%	75%	1,7	50%	10%	0,0	50%	N/A	2,6	50%	30%	0,0	50%	N/A
	Pulp & paper	0,0	80%	N/A	0,0	80%	N/A	0,0	80%	N/A	0,0	80%	N/A	0,0	80%	N/A
	Mineral production (cement)	0,5	90%	90%	6,8	90%	50%	0,6	90%	90%	0,7	90%	90%	0,0	90%	N/A
	Mineral production (lime, plaster, ceramics, glass etc)	0,1	90%	N/A	2,1	90%	40%	0,0	90%	N/A	0,0	90%	N/A	0,0	90%	N/A
	Food processing	0,9	90%	N/A	0,0	90%	N/A	0,0	90%	N/A	0,0	90%	N/A	0,0	90%	N/A
Other	Other	1,4	N/A	N/A				3,4	N/A	N/A	0,0	N/A	N/A	0,0	N/A	N/A
		95,0			**166,7**			**11,9***			**5,2**			**1,0**		

*Note: * CO" emissions in Estonia (EE), have been adjusted in relation to the source (E-PRTR), as the CO2 emission from power and heat sector (20.7 Mt in 2017 according to E-PRTR) is outdated since several fossils fuel-driven plants were close in the past couple of years. Therefore, a more representative number is 7.9 Mt.*

5. OVERVIEW AND EVALUATION OF POTENTIAL SET-UPS FOR TRANSPORT AND STORAGE OF CO2 IN DENMARK

This chapter aims to identify relevant market-based business models that ensure the lowest possible price of Danish CO2 storage and provide an assessment of the competitiveness of the Danish storage sites.

The following sections will go into depth with identifying the North European CO2 streams relevant for Danish storage, possible set-ups for transport and storage of CO2 in Denmark, the competitiveness of the Danish CO2 storage and institutional considerations.

The conclusions from this chapter will create the basis for evaluation of various business models for CO2 storage in Denmark, which will be examined in the next chapter.

5.1 KEY CONCLUSIONS ON THE POTENTIAL SET-UPS FOR TRANSPORT AND STORAGE OF CO2 IN DENMARK

The total volume of up to ~45 MtCO2/y is potentially eligible for import from several North European countries. Denmark has several sites with CO2 storage structures that can be paired with different types of CO2 transportation options to provide various solutions for CO2 storage. Some of these sites and transport set-ups can be combined to increase scale, enhance convenience, or decrease costs. The most cost-efficient set-ups are onshore or nearshore, especially if they are combined with CO2 transport pipelines from regions with large clusters of CO2 emission sources (e.g. Hamburg, DE). Using transport pipelines from such regions enables an opportunity to offer flexible low-priced transport solutions, which enhance the competitiveness of Danish storage solutions. None of the solutions, however, can work by themselves, meaning there is a need for involvement from the state.

When other aspects than costs are considered, both onshore and offshore solutions and both transportation option (pipeline vs sea transportation) have advantages and disadvantages. The onshore solution (especially Havnsø) is located close to the largest domestic CO2 source and can allow flexibility if a gradual build-up is preferred (which is less meaningful in the case of offshores that work best with transport pipeline). On the other hand, the offshore solution can prove to be faster to implement due to a potentially shorter permitting process and the ability to reuse some of the existing infrastructure.

The table below summarises the key conclusions on the potential set-ups for the transport and storage of CO2 in Denmark.

Table 41: Key Conclusions on the overview and evaluation of the potential set-ups for transport and storage of co2 in Denmark

Topic	Key Conclusions
North European CO2 streams relevant for danish storage	The indicative CO2 volumes relevant for Denmark (including domestic CO2 volumes) are estimated at up to ~45 MtCO2/y. The foreign storages that could potentially compete with Danish CO2 storages are mainly the UK and Norway. The import of CO2 is mainly relevant from DE, SE and FI. There is some potential for CO2 import from PL and NL, while no or insignificant import is expected from the Baltics, NO or UK (the latter two have well developed domestic storage projects).
Possible set-ups for transport and storage of CO2 in Denmark	Available options for storage are Gassum (onshore), Havnsø (onshore), Hanstholm (nearshore) and the Northern oil and gas fields in the North Sea (offshore). Available options for transport are shuttle tankers, vessels, and pipelines. Nine possible set-ups for transport and storage og CO2 in Denmark have been identified: Two onshore, two near shore and five offshore. They include different combinations of transport and storage options, meaning that some set-ups will require ports and intermediate storage. In general, the cost comparison shows that onshore storage is the most cost-effective solution (both when pipeline and sea transport is applied), followed by nearshore storage and with offshore storage as the most expensive solution. On the other hand, pipelines provide scale advantage and are thus the most effective transport solution at large-scale.

	In addition to being the least expensive option, the onshore storage has the advantage of being located close to the large domestic CO2 emission sources (Copenhagen area). However, uncertainty whether the site can be used (and thus need for seismic tests and drilling) and the general risk of public opposition can lead to a longer permitting process than in the case of the offshore site. Although the most expensive option, offshore storage offers several advantages, especially in the form of known feasibility and demonstrated tightness. It can be potentially easier to obtain necessary permits (especially compared to onshore sites). Furthermore, some of the existing equipment (platforms and support systems) can be potentially reused, meaning that the offshore solution can be potentially even quicker implementer than the onshore or nearshore solution. Solutions with a pipeline from Germany would provide a more certain CO2 stream from abroad, making it potentially easier (and cheaper) to find investors. On the other hand, this type of solution is only meaningful when the full-scale operations are planned for construction from the beginning, while sea transportation enables small-scale start with gradual build-up. Note that a more gradual start is also possible in the case of the onshore storage, where pipelines from source and other connecting infrastructure can be added afterwards.
Competitiveness of Danish CO2 storage	The competitiveness of CO2 storage is defined by meeting the following criteria: a low-cost solution, with low marginal cost, and the ability to create a solution that allows flexibility Based on the above, it is Ramboll's assessment that Denmark can offer highly competitive solutions that are cost-effective, flexible and a convenient option for the target countries (mainly Germany, Sweden, Finland and potentially Poland). The most cost-competitive solutions include set-ups where large CO2 amounts are contracted via pipeline and those that comprise or combine onshore and nearshore storage sites.
Institutional considerations	It is important to consider varying institutional set-ups of CCS since although CCS is technically feasible and can remove CO2 emissions on a large scale, the business case does not exist without state and Government involvement. To understand the need for state involvement as well as the interplay between different actors and institutional set-ups, several case studies have been studied: the Norwegian full-scale carbon capture, transport and storage demonstration project "Longship", three large CCUS developments in "the UK and the Government's CCS business model considerations" as well as the Porthos CCS project in the Netherlands. See 5.4.2. for the conclusions based on the case studies mentioned above.

5.2 MAPPING OF NORTH EUROPEAN CO2 STREAMS RELEVANT FOR DANISH STORAGE

As assessed in chapter 4, many of the North European countries are expected to apply CCS as a measure to achieve 2030 and 2050 decarbonisation targets. However, not all of these countries have sufficient storage capacity (or an intention to store CO2 domestically) and will therefore need to seek foreign storage.

Based on insights from the previous chapter, this section will provide a mapping of possible CO2 flows between Denmark and Northern Europe, considering potential competing storages, geographical conditions, clusters etc.

The foreign storages that could compete with Danish CO2 storages are mainly the UK and Norway with storages situated offshore in the North Sea. They could potentially compete with a large share of the CO2 export coming from the countries deemed relevant to export CO2 to Denmark (i.e. Germany, Sweden, Finland, The Netherlands but perhaps less likely Poland). Poland could also pose a potential competitive threat and compete with possible CO2 export streams from Finland and Sweden. Of course, this is if they decide to pursue CO2 storage in the future (as mentioned previously, geological storage of CO2 is prohibited until at least 2024 in the country). Competition from the Baltics of CO2 exports is not expected since geological storage is not possible in Estonia, while in Latvia and Lithuania, CO2 storage is currently prohibited. Additionally, in Latvia and Lithuania, the CO2 CCS potential is very limited as policies and climate strategies in these countries are not prioritising CCS and have a preference for CCU if they turn to greenhouse gas removal technologies.[202]

CO2 exports from the following countries are expected to be most relevant:

[202] Ramboll analysis

- Germany: Large volumes of captured CO2 volumes intended for storage in foreign countries are expected, as the country has clearly announced it will not utilise CO2 storage capacities on its own territory. The CO2 volumes are concentrated around the Hamburg area and Northern Germany, where there are numerous power plants and large iron and steel plants. Transport of CO2 from Germany to Denmark by ship and through a pipeline are both feasible possibilities.
- Sweden and Finland: Although there is not a heightened focus on CCS in the countries' climate strategies, compared to the focus on renewable energy and green hydrogen, the pulp and paper industries in these countries are the two largest in Europe. BECCS could therefore become highly relevant for both of these countries so they can close the CO2 emissions mitigation gap to reach their climate neutrality targets. Geological storage is not possible in Finland, and although Sweden has some storage capacities, the country has expressed a preference to export CO2. Moreover, many of the pulp and paper plants are situated close to the coast or rivers (since they use a lot of water resources in their production). It would be potentially effortless to export the CO2 from plants situated close to the coasts with shuttle tankers.

CO2 exports might potentially also come from the Netherlands and Poland:

- The Netherlands: The country has expressed that CCS is a temporary solution to emission removal until CCU and renewables become available at full scale. However, natural gas production is not expected to be phased out in the Netherlands, at least in the short- and medium-term; thus CCS has a large potential to be a key source to mitigate emissions at these plants. The Netherlands has CO2 storage capacities and is planning CCS projects, e.g. the Porthos project is the most known large-scale project. However, other projects are also being planned: Athos in Amsterdam and the Carbon Connect Delta project[203]. Depending on how the Dutch CCS projects progress, there might be some potential for CO2 exports in the short term, industry cluster projects acknowledge that the demand for storing CO2 might exceed the storage capacity and especially if the CCS project deliveries are faced with delays[204]. This means that the export of captured carbon to international carbon storage sites could be necessary for the short-to-medium term. Additionally, the Netherlands have ambitious renewable energy targets, however, they are the country furthest away in the EU from achieving their announced renewable energy targets[205]. To make up for this gap due to the delay of renewables deployment, CCS could be a potential solution to mitigate emissions. Therefore, CO2 emissions from both industry and the power & heat (mainly in the long-term since CCS is limited to industry sectors, to begin with) sector could pose some opportunities to utilise CCS, and some amounts could be exported. It is uncertain to which countries (or how the share of exported CO2 emissions would be split between countries) potential Dutch CO2 export volumes will be transported to. Norway, UK or Denmark could all be potential candidates, and therefore this is also limiting the forecasted CCS volumes from The Netherlands to Denmark. Therefore, Ramboll estimates that there is some potential of storing CO2 from the Netherlands in Denmark, yet the potential is smaller than the CO2 streams coming from Germany, Finland, and Sweden.
- Poland: The country has CO2 storage capacities, which could become relevant in the future and potentially also be cheaper than exporting CO2 to other countries. However, they have not announced interest in utilising their own CO2 capacities, and this is prohibited until 2024. And thus, there is some potential for CO2 exports from Poland, but this is highly dependent on political decisions, and the unfolding of these are highly uncertain.

Norway and UK storages could potentially compete for all the CO2 volumes described above.

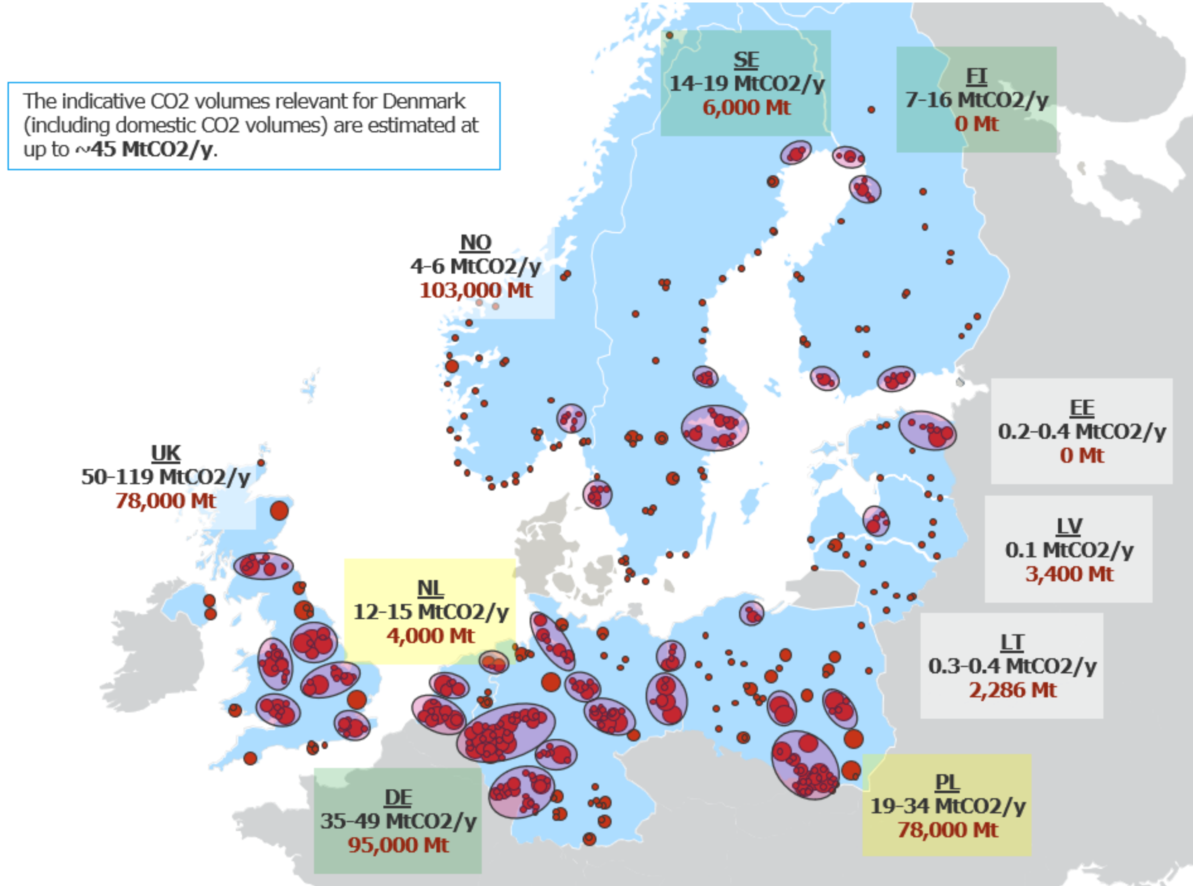
The potential of CO2 exports from the Baltic countries is limited or even deemed insignificant. As mentioned, the country's policies are not focusing or prioritising CCS, and the CCS potential of CO2 for CCS are limited. Nevertheless, the governing party in power changes often in these countries and especially the Latvian and Lithuanian Government (depending on the ruling political party) have shifted between allowing CO2 storage and prohibiting it, which poses uncertainty with

[204] European Commission, "Candidate PCI projects in cross-border carbon dioxide transport networks"

[205] Eurostat – "Renewable energy statistics"

regards to the countries' positioning towards CCS. Nevertheless, CCU is preferred above CCS in all of the Baltic countries.[206]

Figure 10: Overview of North European CO2 streams relevant for Danish storage



Source: Ramboll analysis, E-PRTR database

The indicative CO2 volumes relevant for Denmark (including domestic CO2 volumes) are estimated at up to ~45 MtCO2/y. Note that the volumes presented below are not final and only potential volume estimates subject to change since they depend on future policy decisions and climate strategies in different countries. This poses uncertainties since the political landscape and policies change, making it difficult to forecast the CO2 CCS potential. Additionally, the imported CO2 volumes are also dependent on the development of CO2 prices, competition from foreign CO2 storages and Denmark's own CO2 storage capacity developments.

Table 42: Estimated CO2 volume that can be potentially imported to DK (MtCO2/y)

Country	Total CO2 intended for CCS (MtCO2/y)[207]	Comment	Potential import to DK (MtCO2/y)
Germany	42	~20% of all emissions are from clusters in Northern Germany; Since capturable amount only includes large CO2 sources, an even higher share is expected from these clusters. Consequently, Ramboll estimates that up to 35% of emissions are within clusters; Additional CO2 can be imported via shuttle tanker transport. Due to general constraints, i.e. that some CO2 can be difficult to access or not feasible for dispersed sources or sent to other competing countries, Ramboll makes the assumption that up to ~50% of the estimated CO2 volumes can be potentially transported to Denmark.	~21

[206] Expert interview; Tallinn University of Technology

[207] Calculated as an average annual value for the years from the start point (e.g. 2025 for UK and 2030 for some other countries) and up to 2050

<table>
<tr><td>Finland</td><td>12</td><td rowspan="2">The majority of capturable emissions comes from the pulp & paper industry, which are often located close to coastline or rivers, and thus easily accessible. For financial estimates in this chapter, we assume that up to ~75% of CO2 volumes intended for CCS will be transported to foreign storages, including Denmark, of which half of the 75% can potentially be exported to Denmark. Only shuttle tanker transport applies.</td><td>~5</td></tr>
<tr><td>Sweden</td><td>17</td><td>~6</td></tr>
<tr><td>The Netherlands</td><td>14</td><td>Although the Netherlands have their own storage capacities, there might be potential for CO2 export. The majority of emission sources are close to coastline or rivers (and thus accessible), which makes them somewhat feasible for CO2 export. However, both Norway and the UK, in addition to Denmark, could compete for these exported CO2 volumes. Based on these conditions, Ramboll estimates that 20% of estimated CCS volume will be imported to Denmark; Shuttle tanker transport applies for onshore and nearshores storage solutions, while either shuttle tanker or pipeline applies for the offshore solution.</td><td>~3</td></tr>
<tr><td>Poland</td><td>27</td><td>In Poland, there are some large energy clusters in the central and southern part of the country. However, a large share of the plants in the south are coal-driven and thus not relevant since the large majority will be phased out. Although CO2 could potentially be transported from the central part of the country (inland locations) via rivers, there is a high probability that some of the CO2 is too difficult to access or not feasible for dispersed sources. Existing and planned natural gas plants are considered most relevant – these are relatively spread all over the country. Further, emissions from industry are highest in the south and south-eastern parts of the country. Consequently, for financial estimates, we make a conservative assumption that ~25% of the estimated impact will be transported to Denmark. Only shuttle tanker transport applies since CO2 transported by a pipeline is deemed too risky to construct if Poland starts to invest in their own storages.</td><td>~7</td></tr>
<tr><td colspan="3">Total CO2 that can be imported to DK (MtCO2/y)</td><td>~40</td></tr>
</table>

In terms of domestic CO2 sources in Denmark, we have estimated them to be at about ~5 MtCO2/y (~3 MtCO2/y from the Copenhagen area and ~2 MtCO2/y from the Aalborg area)[208]:

- CO2 clusters are present in the Copenhagen area since it is an urban area with CO2 volumes coming from, e.g., Amager Bakke, Amagerværket, HC Ørsted power plant, Avedøre power plant, Roskilde waste incineration plant and others
- In Aalborg, situated in Northern Denmark, there are also CO2 sources from Aalborg Portland, a cement plant and Nordjyllandsværket power plant
- Other potential CO2 sources could be captured in the Aarhus area, which is also urbanized.

5.3 POSSIBLE SET-UPS FOR TRANSPORT AND STORAGE OF CO2 IN DENMARK

The full CCS chain consists of several elements:

- Capture at source
- Compression/liquefaction
- Intermediate storages at export – option at capture site and/or at a storage site
- Transportation: pipeline transportation or ship (shuttle tanker of the vessel)
- Intermediate storages close to storage - option
- Geological storage

This section will map available options for transport and storage of CO2 in Denmark (last three of the above-listed bullets), i.e. part of the CCS value chain within Denmark's scope. Different options will then be compiled into different possible set-ups, paired with estimated costs and compared to identify the most cost-effective solutions.

Options for transport and storage in Denmark, as well as cost estimates, are based on Catalogue of Geological Storage of CO2 in Denmark by Danish Energy Agency and Ramboll (2021) and Catalogue on Technology Data for Energy Transport published by the Danish Energy Agency and Energinet (2017, updated in 2020), supplied with Ramboll's technical and commercial insights (e.g. in relation to scaling up of costs for large-scale scenarios).

[208] Danish Energy Agency/Ramboll - Catalogue of geological storage of co2 in Denmark

Estimates such as costs, capacity etc., can only be clearly defined after design and data collection has been performed and should therefore be treated as indicative and with some uncertainty.

Box 3 – A note on set-ups

All storage and transport set-ups presented in this chapter are potential illustrative scenarios only. This also pertains to the suggested storage and pipeline locations as well as the shipping routes. Thus, the set-ups are not to be regarded as definitive rather as potential suggestions for feasible scenarios. The set-ups take a point of departure in the Catalogue of Geological Storage of CO2 in Denmark by Danish Energy Agency and Ramboll (2021).

5.3.1 Available options for transport and storage of CO2 in Denmark

5.3.1.1 Suitable storage sites in DK

Based on Ramboll's previous analyses[209], and mapping by GEUS, three different generic scenarios are assessed for suitable storage sites in DK: onshore saline aquifers, near shore saline aquifers and offshore depleted oil/gas fields.

Ramboll finds all geological storage scenarios analysed in this study to be feasible and realistic[210]. However, the present report should not be used for decision making for the development of concrete storage projects.

Onshore and nearshore saline aquifers: An aquifer is a porous sandstone with water naturally present in the pores in the sand. Consequently, injected carbon dioxide can behave the same way water does (occupy the pores) or potentially be dissolved into the water over a longer time. The system consists of an injection well, injection pump for additional compression, monitoring in the well cellar and different monitoring systems spread out on the surface of the anticipated delineation of the CO_2 plume[211]. The below geological structures are considered to be realistic options for onshore CO_2 storage in Denmark[212]:

Onshore structures:

- *North Jylland:* Vedsted structure (storage capacity as published by GEUS: 162 Mt); The structure is mature for further development.
- *East Jylland*: Gassum structure (630 Mt), Voldum structure (288 Mt) and Paarup structure (91 Mt); All these three structures could be developed as storage options.
- *Sjælland:* Havnsø structure (927 Mt); A large and promising structure, that has not been drilled.

Near shore structures:

- Hanstholm structure (2,753 Mt); The expected injection site is located some 30-50 km offshore from the Port of Hanstholm. A similar but very immature type of near shore storage option may exist in the southern part of the North Sea (off the coast of Esbjerg), with the geological structure located some 100 km offshore.
- Røsnæs structure (227 Mt); Located under the Great Belt with a smaller part below the tip of Røsnæs. This means that wells potentially could be drilled from land.

Offshore depleted oil/gas fields[213]: Oil & gas has been produced from the Danish North Sea since the early 1970s, and some of the fields are approaching the end of field life. The depleted northern sandstone fields in the Central Graben are at this point in time considered most suitable for the timely development of geological CO2 storage. Chalk fields may be relevant later: requires re-use of long horizontal wells and wellhead platforms,

The different storage options are presented in the figure below:

[209] Catalogue of geological storage of CO2 in Denmark, Ramboll/DEA, 2021 and CCUS Technology Catalogue, Ramboll, 2020

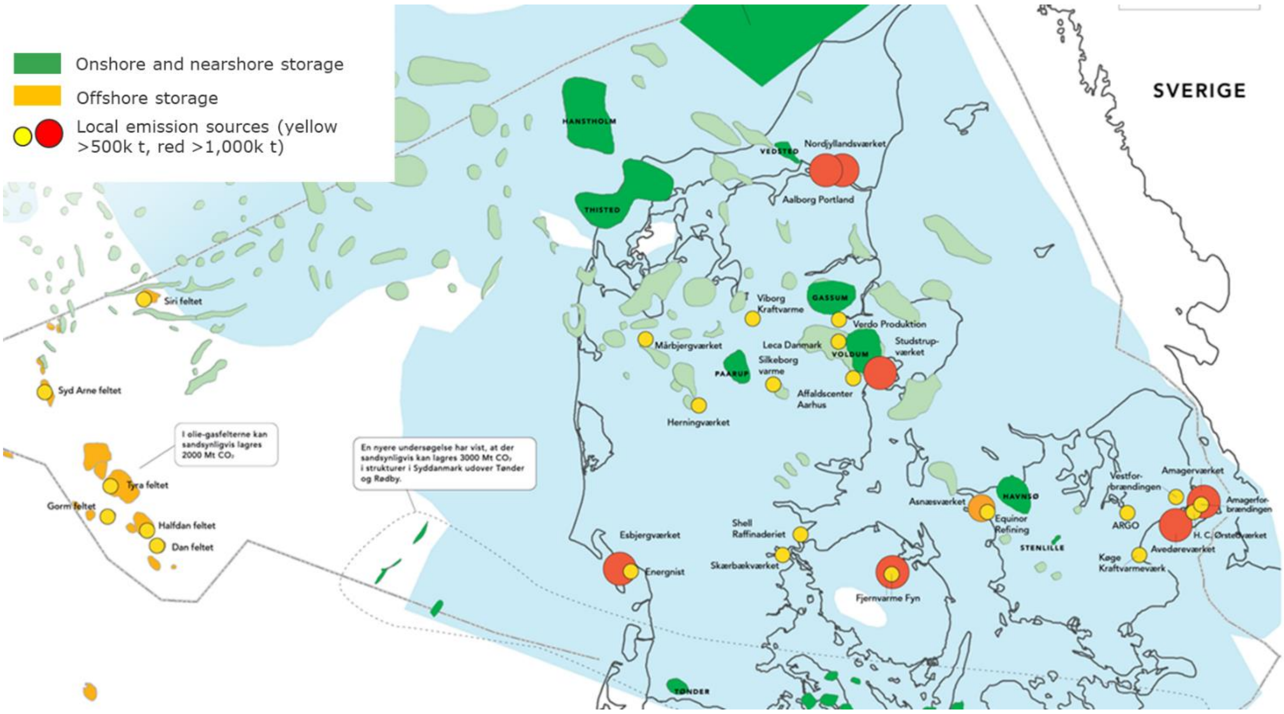
[210] Catalogue of geological storage of CO2 in Denmark, Ramboll/DEA, 2021

[211] S. M. Thomsen and J. Flørning, 'CO2 neutral energy system utilizing the subsurface', Copenhagen, 2019

[212] Catalogue of geological storage of CO2 in Denmark, Ramboll/DEA, 2021

[213] Catalogue of geological storage of CO2 in Denmark, Ramboll/DEA, 2021

Figure 11: Overview of potential CO2 storage options in Denmark



Source: GEUS

5.3.1.2 Available options for the transport of CO2 to the storage site[214]

CO2 emission sources and suitable geological storage sites are likely to be geographically separated. Consequently, the realisation of carbon capture storage will nearly always involve the transportation of CO_2. The main technologies deemed suitable for the transport of CO2 are:

- Pipeline transport
- Ship transport (shuttle tanker transport combined with intermediate storage or transport by vessels equipped with storage facilities)
- Road transport

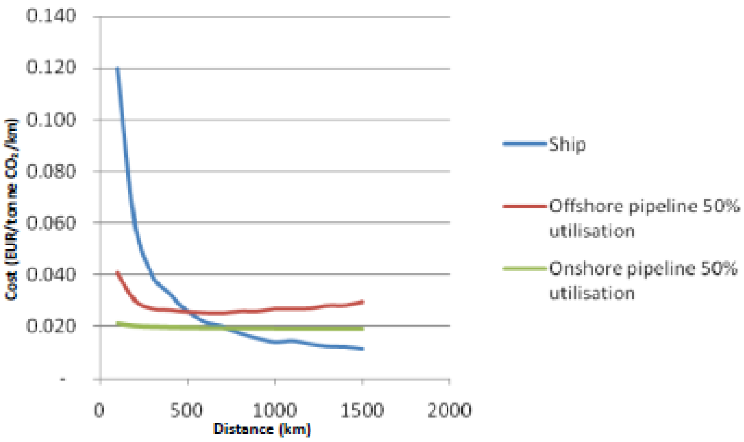
The different modes of transportation have varying advantages and disadvantages. Take CO2 transport by a shuttle tanker; this provides more flexibility than pipeline solutions since the routes of transport can be easily adjusted. This is particularly beneficial because transportation is needed for a new CO2 source location or storage site location. Further, the transport capacity can also be adjusted depending on demand. Standard carrier shuttle tankers can also be used for other transport of goods /e.g. LNG), if the need for transporting CO2 decreases.

On the other hand, shuttle tanker transport of CO2 is more expensive than pipeline transport for short to medium distances and costly CO2 terminals and intermediate storage facilities are also required for this mode of transportation. Thus, both the shuttle tanker's capital expenditure and the terminal fees are fixed regardless of the distances. If large volumes of CO2 (providing economies of scale) are transported or if CO2 point sources are located inland, then a pipeline solution will be the most cost-efficient option. As shown in the graph below conducted by ZEP[215], pipeline transport is estimated to be more cost-efficient for transport distances of 500-700 km, after which shuttle tanker becomes economically more feasible.

[214] Catalogue on Technology Data for Energy Transport published by the Danish Energy Agency and Energinet (2017, updated in 2020)

[215] The Cost of CO_2 Transport – Post-demonstration CCS in the EU. ZEP report 2010.

Figure 12: Cost of CO_2 transport (EUR/tonne/km, 2010 cost level) by pipeline at 50% capacity and by ship at 100% capacity (including terminal) for 10 MtCO2/y



Note: In the research below, transport of 10 MtCO2/y was compared between ships (shuttle tanker) and pipeline. Further, the study underlies the assumption that pipeline utilisation is 50%. Different assumptions change the intersection point of when which transport mode becomes more cost-efficient. Source: ZEP, Catalogue on Technology Data for Energy Transport published by the Danish Energy Agency and Energinet (2017, updated in 2020).

When CO2 sources are concentrated (e.g. in the form of an industry cluster), the most uncomplicated composition would be a capture, compression, pipeline transportation and storage. Suppose several sources are combined and cannot be connected to a pipeline. In that case, there will be a need for intermediate storage above the ground, which is connected to the permanent storage by a pipeline for onshore/nearshore activities or shuttle tankers for offshore activities.

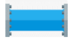
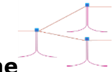
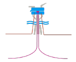
5.3.2 Mapping of possible set-ups for transport and storage of CO2 in Denmark

Possible set-ups for CO2 transport and storage are presented in this section. They have been created based on Ramboll's expertise within CCS and with inspiration from ongoing CCS projects in Norway, the Netherlands, and Great Britain. Additionally, experience from the oil and gas industry and knowledge from the district heating industry have been used to qualify the set-ups presented below. This includes but is not limited to the know-how of large volume transport of gas and liquids using pipelines, ships and trucks.

In the table below, nine set-ups in total are presented: Two onshore, two near shore and five offshore (presented in Table 43 below, and also visualised in Figure 13). They include different combinations of transport and storage possibilities, meaning some set-ups will require ports and intermediate storage (e.g. set-up #3). In contrast, other set-ups are based exclusively at sea (e.g. set-up #7).

Set-ups including pipelines from Northern Germany or the Netherlands are still open to shuttle tanker transport from these countries. This means that CO2 transportation via shuttle tankers from these countries is expected to continue but decrease to some extent to take advantage of the decrease in marginal cost enabled by a pipeline.

Table 43: Overview of potentially relevant set-ups for transport and storage of CO2 to Denmark

 **Shuttle tanker**  **Vessel**  **Permanently moored FSU**  **Port**  **Pipeline**  **Well pad**  **Well head platform**

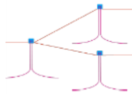
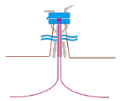
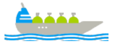
<table>
<tr><th>Storage type</th><th>Potential site name (and capacity)</th><th>Assumed max. injection capacity per year</th><th>Set-up #</th><th>CO2 Transport from source</th><th>Intermediate storage and preparation facilities</th><th>Transport from intermediate storage to well</th><th>Injection site</th><th>Description</th></tr>
<tr><td rowspan="3">Onshore</td><td rowspan="3">Gassum (630 Mt)
Or
Havnsø (927 Mt)</td><td rowspan="3">10 MtCO2
(Gassum)</td><td>1</td><td></td><td rowspan="3"></td><td rowspan="3"></td><td rowspan="3"></td><td>- Shuttle tankers transport CO2 from ports near emissions sources to a port near the storage site. The CO2 is transported from the port to the injection site via pipeline, where it is injected into the onshore storage site</td></tr>
<tr><td rowspan="2">2</td><td></td><td rowspan="2">- Shuttle tankers transport CO2 from ports near emissions sources to a port near the storage site.
- Additionally, CO2 from CPH is transported via pipeline to the port
- The CO2 is transported from the port to the injection site via pipeline, where it is injected into the onshore storage site
- Assumption: 40%-80% (4MtCO2/y) will come from DK/CPH through the pipeline, and the remaining CO2 via sea from other sources</td></tr>
<tr><td>
From DK/CPH</td></tr>
<tr><td rowspan="3">Nearshore</td><td rowspan="3">Røsnæs (227 Mt)
or
Hanstholm (2,753 Mt)</td><td rowspan="3">10 MtCO2
(Hanstholm)</td><td>3</td><td></td><td rowspan="3"></td><td rowspan="3"></td><td rowspan="3"></td><td>- Shuttle tankers transport CO2 from ports near emissions sources to a port near the storage site
- The CO2 is transported from the port to the injection site via pipeline, where it is injected into the nearshore storage site</td></tr>
<tr><td rowspan="2">4</td><td></td><td rowspan="2">- Shuttle tankers transport CO2 from ports near emissions sources to a port near the storage site
- Additionally, CO2 from CPH is transported via pipeline to the port
- The CO2 is transported from the port to the injection site via pipeline, where it is injected into the nearshore storage site
- Assumption: 40%-80% (4MtCO2/y) will come from DK/CPH through the pipeline, and the remaining CO2 via sea from other sources</td></tr>
<tr><td>
From DK/CPH</td></tr>
</table>

Figure continues on the next page

Storage type	Potential site name (and capacity)	Assumed max. injection capacity per year	Set-up #	CO2 Transport from source	Intermediate storage and preparation facilities	Transport from intermediate storage to well	Injection site	Description
Offshore	Depleted oil and gas field in the North Sea (estimated ~2,000 Mt)	**10 MtCO2**	**5**					- Shuttle tankers transport CO2 from ports near emissions sources to a port near the storage site - CO2 is transported from the port to the injection site via pipeline, where it is injected into the offshore storage site
			6					- Vessels transport CO2 from ports near emissions sources to injection sites - The CO2 is transferred directly to the offshore storage site, where it is injected
			7					- Shuttle tankers transport CO2 from ports near emission sources to a permanently moored FSU near the storage site - The CO2 is directly transferred from the FSU to the injected site, where it is injected into an offshore storage site
			8	From DE				- Shuttle tankers transport CO2 from ports near emissions sources to a port near the storage site - Additionally, CO2 from Northern Germany is transported to the port via an onshore pipeline - CO2 is transported from the port to the injection site via pipeline, where it is injected into the offshore storage site - Assumption: 4-5 MtCO2/y will come from DE through a pipeline, and the remaining CO2 via sea from other sources
			9	From SE, FI, PL & DK (rest) From DE From NL				- Shuttle tankers transport CO2 from ports near emission sources in DK, SE, FI & PL to a port near the storage site. From the port, CO2 goes to the injection site via pipeline - Additionally, pipelines from Northern Germany and the NL transport CO2 from nearby CO2 emissions clusters to the injection site via pipelines. From the injection site, the CO2 is injected into the offshore storage site - Assumption: 4-6 MtCO2/y will come from DE+NL via pipeline, and the remaining CO2 via sea from other sources

Note: Shuttle tankers are considered pure transport vehicles, meaning they do not have cooling equipment and storage preparation equipment needed to connect directly to an injection site. As a result, shuttle tankers need to unload CO2 into intermediate storage near refrigeration and storage preparation equipment before it can be transferred to an injection site; Vessels can be used for transport and carry cooling and storage preparation equipment. This means they can connect directly to injection sites; Permanently moored FSU stations are considered stationary and cannot be moved. Shuttle tankers will transport CO2 to the station, which will prepare the CO2 for storage before sending it to the injection site; Well pad: An area that is cleared or prepared for the drilling of wells, the area is a fenced-off area with drainage and other facilities to allow safe and environmentally friendly drilling of wells; Wellhead platform: An offshore steel structure for the support of production and/or injection wells and associated support systems; Injection well: A well for injection of CO2 into a subsurface reservoir; Intermediate CO2 storage: A site with pressurised and cooled tanks for storage of liquified CO2; Permanently moored vessel: A so-called floating storage unit (FSU) equipped with the injection facilities; **Source:** Ramboll analysis

Figure 13: Illustration of different set-ups for ups for transport and storage of CO2 to Denmark (see appendix for illustration of each set-up separately)

Note: Ports (especially foreign) are only illustrative suggestions for where CO2 could depart by ship transport.
Source: Ramboll analysis; Ramboll & the Danish Energy Agency, "Catalogue of Geological CO2 Storage in Denmark."

It is Ramboll's assessment that no single storage site in Denmark is capable of handling 45 MtCO2/y alone. Meaning, that if a capacity of up to 45 MtCO2/y is desired, a combination of the set-ups presented below must be used. The offshore storage sites do theoretically have adequate storage capacity. However, even though they have the theoretical capacity to store the 45 MtCO2/y over a period of 30 years (1350 Mt in total), the maximum injection rate of the sites is rated at 10 MtCO2/y. This is due to a large amount of the capacity being situated in depleted oil and gas field that are in chalk reservoirs not suited for CO2 injection. Injection of CO2 into these fields would require a large number of wells raising the price of CO2 injection to higher levels[216]. Alternatively, large offshore aquifers could be utilised, however, they remain largely unmapped, meaning there is a large amount of uncertainty regarding their storage capacity and possible injection rates. As a result, offshore aquifers have not been considered in this report.

Note that shuttle tankers are currently not large enough to handle the estimated amounts of CO2 without deploying a large number of shuttle tankers. Set-ups below assume that larger shuttle tankers (20,000 net tonnages or even above) will be available at the time storage is operationalised. Larger shuttle tankers would require larger ports, which means that shuttle tanker sizes will also vary depending on the size of the port near emissions sources. However, some ports will remain small, which means large intermediate ports could be established where smaller shuttle tankers from smaller ports could transport and unload CO2. Larger shuttle tankers could then transport the aggregated CO2 from the intermediate port to the final port.

Furthermore, the set-ups are built upon the assumption that all pipeline, intermediate storage, and injection site infrastructure will have to be constructed. Some infrastructure can theoretically be re-used; however, given the large CO2 volumes assumed in this report, this is deemed a less efficient and a more complex solution and will therefore not be considered.

More scenarios were considered, however, they were deemed technically, economically, or politically infeasible for the time being. Particularly pipelines from Northern Germany and the Netherlands were not included in the onshore and nearshore set-ups as the pipelines would have to extend further, which was deemed too expensive.

[216] Ramboll expert

5.3.3 Overview costs for transport and storage of CO2 in Denmark per set-up

To assess which solution(s) are the most cost-effective, each of the set-ups described in 5.3.2 has been matched with respective costs for transportation and storage of CO2 in Denmark.

Cost estimates include relevant considerations, such as type of storage and transportation technology applied, quantities of CO2 expected through pipelines and sea, respectively, and distance from the source. Cost estimates in this report are based on assumptions from Catalogue of Geological Storage of CO2 in Denmark by the Danish Energy Agency and Ramboll (2021) and the Catalogue on Technology Data for Energy Transport published by the Danish Energy Agency and Energinet (2017, updated in 2020).

Costs have been compiled for two scenarios: 5 MtCO2/y and 10 MtCO2/y. In order to secure full comparability across presented set-ups, the cost comparison is only performed for the scenario with 5 MtCO2/y, as assumptions underlying the 10MtCO2/y scenario are more set-up specific. For example, the amount of CO2 transported via pipeline in set-up 2 (pipeline from Copenhagen to onshore storage and remaining share transported from other sources by sea) is constant in both scenarios, i.e. it amounts to 80% at 5 MtCO2/y and only 40% at 10 MtCO2/y. While set-up 1 is 100% sea transport in both scenarios (5 MtCO2/y and 10 MtCO2/y). However, it is our opinion that conclusions drawn from the cost benchmark at 5 MtCO2/y will also be applicable for larger scenarios. Overview of cost estimates for 10 MtCO2/y is provided in the appendix.

The cost comparison shows that onshore storage is the most cost-effective solution (both when pipeline and sea transport is applied). On the other hand, a pipeline provides a scale advantage and is thus the most effective transport solution at large-scale (i.e., e.g. 5 MtCO2/y). More specifically, the following conclusions can be drawn:

- Set-up 2 (focus on pipeline transport from Copenhagen to onshore storage) is the least expensive
- Set-up 4 (focus on pipeline transport from Copenhagen to nearshore storage) is the least expensive nearshore option but more expensive than onshore storage
- Set-ups comprising offshore storage are more expensive than those with both onshore and nearshore solutions
- Set-up 8 (focus on pipeline transport from DE) is the least expensive of all offshore storage options

Storage cost comprises cost to establish the storage (e.g., pre-FID studies, the pipeline from port to storage, injection equipment, monitoring equipment etc.) and operations (incl. organisation, power etc.). In the calculation for onshore storage, it is assumed that the Havnsø storage site, accessed through Kalundborg harbour, will be used due to the estimated size, proximity to Amager Forbrænding and the current momentum of the site. For nearshore storage, it is assumed that the Hanstholm storage site, accessed through Hanstholm harbour, will be used due to the size of the estimated storage capacity. Offshore storage will be assumed to be in the Northern part of the North Sea oil and gas fields, accessed through Esbjerg harbour, due to the sites' geological nature, meaning fewer wells are needed for the same flow rate.

Transport cost covers the cost of transporting CO2 from ports near emission sources in five Northern European countries and domestically in Denmark, to a Danish intermediate storage facility near a storage site, either through the pipeline or by sea. Pipeline transportation includes CAPEX (for both pipeline and power stations), maintenance, monitoring and power costs. Sea transportation includes CAPEX (for ships and intermediate storage at export ports), maintenance and fuel. Note that the cost for transport by the sea does not include harbour fees or the cost for liquefaction (which is typically included at the CO2 capture plant).

CO2 transport costs from shuttle tankers are included in the business cases in chapter 6, although this could potentially be paid by the emitter or split between the emitter and the CO2 storage provider. In the case that Denmark pays for the export countries' transport of CO2, the export countries will receive favourable conditions – especially in the less expensive onshore storage solution option. The cost of covering export countries' transport might be transferred to Danish emitters, making it more expensive for them, and Danish emitter might choose storage solutions in competing countries. If CO2 is imported at a large-scale, it could be more feasible to cover the export countries' transport costs since the price could come down with economies of scale.

Note that there is still a lot of uncertainty about costs and performance, as only a few carbon storage projects have been implemented in Europe, and mostly in association with oil and gas production. In addition to the general cost levels, there is also uncertainty with respect to the delimitation of the operator's responsibility after closing of the storage (and costs for e.g. monitoring) and to the technical development (e.g. injection rates in different types of reservoirs as well as the choice of steel material, e.g. wells), which can both impact costs. Initially, we assume that a conservative approach will be used, which may increase the cost for the first large-scale projects. In line with operational experience, there may be a decline in cost due to a more optimized design. The actual capacity may prove to be larger than the nameplate capacity.

Box 4 – A note on costs

All individual costs inputs i.e. transportation and storage costs presented in this chapter and utilised in the business cases in chapter 6 are not levelized costs.

Details regarding assumptions used for cost estimation in each set-up are described in Appendix.

Table 44: Cost for the different set-ups for transport and storage of CO2 in Denmark

		Set-up # 1 **Onshore**; Shuttle tankers -> port -> storage site via pipeline	Set-up # 2 **Onshore**; shuttle tankers & pipeline (from CPH) -> port -> storage site via pipeline	Set-up # 3 **Nearshore**; Shuttle tankers -> port -> storage site via pipeline	Set-up # 4 **Nearshore**; Shuttle tankers & pipeline (CPH) -> port -> storage site via pipeline	Set-up # 5 **Offshore**; Shuttle tankers -> port -> storage site via pipeline	Set-up # 6 **Offshore**; Vessels -> injection site	Set-up # 7 **Offshore**; Shuttle tankers -> permanently moored FSU -> injection site	Set-up # 8 **Offshore**; Shuttle tankers & pipeline (from DE) -> port -> storage site via pipeline	Set-up # 9 **Offshore**; Shuttle tankers (SE, FI, PL & DK) -> port -> storage via pipeline; Pipeline from DE & NL -> storage
		MDKK 5 MtCO2/y	**MDKK** 5 MtCO2/y	**MDKK** 5 MtCO2/y	**MDKK** 5 MtCO2/y	**MDKK** 5 MtCO2/y	**MDKK** 5 MtCO2/y	**MDKK** 5 MtCO2/y	**MDKK** 5 MtCO2/y	**MDKK** 5 MtCO2/y
STORAGE	**Pre-FID Cost**	**195**	**195**	**370**	**370**	**120**	**300**	**120**	**120**	**120**
	2D Seismic	90	90	90	90	70	150	70	70	70
	Basline studies	20	20	20	20	20	60	20	20	20
	Appraisal well	55	55	230	230	n/a	n/a	n/a	n/a	n/a
	FEED Studies	10	10	10	10	10	30	10	10	10
	Approvals	20	20	20	20	20	60	20	20	20
	CAPEX	**2.315**	**2.315**	**4.065**	**4.065**	**4.770**	**2.980**	**3.855**	**4.770**	**4.770**
	Intermediate storage	180	180	180	180	180	n/a	n/a	180	180
	Injection plant	420	420	420	420	390	340	390	390	390
	Pipeline	140	140	350	350	1.750	n/a	n/a	1.750	1.750
	Injection wells	1.575	1.575	2.835	2.835	1.925	1.960	1.925	1.925	1.925
	Wellhead platform	n/a	n/a	280	280	525	275	525	525	525
	Mooring and loading system	n/a	n/a	n/a	n/a	n/a	405	375	n/a	n/a
	Purpose built CO2 carrier/FSU	n/a	n/a	n/a	n/a	n/a	n/a	640	n/a	n/a
	Accumulated OPEX	**2.938**	**2.938**	**4.512**	**4.512**	**9.101**	**13.242**	**11.443**	**9.101**	**9.101**
	Base organisation	175	175	350	350	525	525	525	525	525
	Intermediate storage	223	223	223	223	223	n/a	n/a	223	223
	Injection plant	521	521	521	521	967	844	967	967	967
	Pipeline	38	38	95	95	473	n/a	n/a	473	473
	Injection wells	427	427	825	825	527	608	527	527	527
	Monitoring	670	670	920	920	920	920	920	920	920
	Power	884	884	884	884	3.036	3.450	3.036	3.036	3.036
	Wellhead platform	n/a	n/a	694	694	2.430	4.650	2.430	2.430	2.430
	Standby vessel	n/a	n/a	n/a	n/a	n/a	1.240	620	n/a	n/a
	Mooring and loading system	n/a	n/a	n/a	n/a	n/a	1.005	831	n/a	n/a
	Purpose built CO2 carrier/FSU	n/a	n/a	n/a	n/a	n/a	n/a	1.587	n/a	n/a
	Closure costs	**805**	**805**	**1.311**	**1.311**	**1.435**	**1.122**	**1.275**	**1.435**	**1.435**
	Abandonment cost (ABEX)	405	405	711	711	835	522	675	835	835
	Post-Closure Cost/Monitoring	400	400	600	600	600	600	600	600	600
TRANSPORT – SHUTTLE TANKER/ VESSEL	**CAPEX**	**3.669**	**2.723**	**3.669**	**2.348**	**3.669**	**4.542**	**3.669**	**2.723**	**2.723**
	Transport shuttle	1.419	473	1.419	473	1.419	n/a	1.419	473	473
	Vessel	n/a	n/a	n/a	n/a	n/a	2.292	n/a	n/a	n/a
	Export intermediate storage	2.250	2.250	2.250	1.875	2.250	2.250	2.250	2.250	2.250
	Accumulated OPEX	**4.412**	**2.607**	**4.499**	**2.316**	**4.587**	**5.759**	**4.575**	**2.659**	**2.668**
	Transport ships fixed O&M	3.738	2.461	3.738	2.157	3.738	n/a	3.738	2.461	2.461
	Vessels fixed O&M	n/a	n/a	n/a	n/a	n/a	4.917	n/a	n/a	n/a
	Fuel costs	673	146	761	159	848	843	837	198	207
TRANSPORT – PIPELINE (from port or from emission source)	**CAPEX**	**-**	**467**	**-**	**2.100**	**-**	**-**	**-**	**1.108**	**6.417**
	Onshore pipeline	n/a	350	n/a	1.050	n/a	n/a	n/a	875	n/a
	Offshore pipeline	n/a	n/a	n/a	700	n/a	n/a	n/a	n/a	5.950
	Pumping station	n/a	117	n/a	350	n/a	n/a	n/a	233	467
	Accumulated OPEX	**-**	**203**	**-**	**905**	**-**	**-**	**-**	**506**	**2.627**
	Onshore pipeline fixed O&M	n/a	95	n/a	284	n/a	n/a	n/a	236	n/a
	Offshore pipeline fixed O&M	n/a	n/a	n/a	189	n/a	n/a	n/a	n/a	1.607
	Power cost	n/a	108	n/a	432	n/a	n/a	n/a	270	1.020
Total cost per ton, DKK/ton		106	91	136	133	175	207	185	166	221
*hereof storage		46	46	76	76	114	131	124	114	114
*hereof transport		60	44	61	57	61	76	61	52	107

Source: Catalogue of Geological Storage of CO2 in Denmark by Danish Energy Agency and Ramboll (2021) and Catalogue on Technology Data for Energy Transport published by the Danish Energy Agency and Energinet (2017, updated in 2020), supplied with Ramboll's technical and commercial insights (e.g. in relation to scaling up of costs for large-scale scenarios)

5.3.4 Other advantages and disadvantages of the different set-ups

In the previous sections, the different set-ups were evaluated based exclusively on costs. This section aims to provide an overview of other aspects of the identified aspects, both those in favour and disadvantages.

In addition to being the least expensive option (as described in the previous section), the onshore storage has the advantage of being located close to the large domestic CO2 emission sources (Copenhagen area). However, uncertainty whether the site can be used (and thus need for seismic tests and drilling) and the general risk of public opposition can lead to a longer permitting process than in the case of the offshore site.

Although the most expensive option, offshore storage offers several advantages, especially in known feasibility and demonstrated tightness. It can be potentially easier to obtain necessary permits (especially for the onshore site). Furthermore, some existing equipment (platforms and support systems) can potentially be reused, meaning that the offshore solution can be implemented even faster than the onshore or nearshore solution.

Solutions with a pipeline from Germany would provide a more certain CO2 stream from abroad, making it potentially easier (and cheaper) to find investors. On the other hand, this type of solution is only meaningful when the full-scale operations are planned for construction from the beginning, while sea transportation enables small-scale start with gradual build-up. Note that a more gradual start is also possible in the case of the onshore storage, where pipelines from source and other connecting infrastructure can be added afterwards.

The table below provides a detailed overview of the advantages and disadvantages of each set-up for transport and storage of CO2 in Denmark.

Table 45: Overview of other (non-cost based) advantages and disadvantages of the different set-ups

Set-up		Advantages	Disadvantages
Onshore	**#1, #2**	- Havnsø is an attractive location for storage due to its close proximity to large emission sources in the Copenhagen area. Furthermore, it is close to a deep-water port, making it feasible for transport with large shuttle tankers (assumption for this project)	- Since the site has not yet been drilled, it is not 100% certain that the site can be used for CO2 storage. It is, therefore, necessary to carry out seismic surveys as well as appraisal drilling, which can extend the timeline (and also meet public opposition due to the onshore testing equipment) - Due to the onshore location and possible public opposition, permitting process can be longer (and more uncertain) than for the offshore storage
Nearshore	**#3, #4**	- Pumping equipment can be located onshore, making this solution less expensive than the offshore solution (as the power connection can be done onshore and does not need to be solved offshore) - Similar to Havnsø, Hanstholm is located close to a deep-water port that can receive large shuttle tankers	- Nearshore reservoirs have not yet been drilled, and it is not 100% certain that they can be used for CO2 storage. However, the seismic equipment can be placed offshore, meaning it is easier and can meet less public opposition than onshore - Although CO2 can be sourced from the Aalborg area, the distance to the largest source of domestic emissions (Copenhagen area) is much longer than for the onshore storage, making it more expensive to transport
Offshore	**All offshore-based set-ups**	- Tightness (and thus feasibility) of the geological system has been already demonstrated, e.g. in connection with EOR (Enhanced Oil Recovery) in North America. Seismic studies still need to be carried out; however, this process is expected to be shorter than is the case for onshore or offshore storage sites. - Furthermore, some of the existing equipment can be reused (e.g. wells, platforms, parts of the topside facilities, support systems). Together with the above, this means that offshore storage can potentially be	- Although CO2 can be sourced from the Aalborg area, the distance to the largest source of domestic emissions (Copenhagen area) is much longer than for the onshore storage, making it more expensive to transport

		deployed faster/earlier than the onshore and nearshore solutions. - Due to long-distance to shore and lower environmental impact, less public opposition is expected and potentially easier to obtain necessary permits.	
	#6, #7	- Injection directly from vessels or FSU requires simpler infrastructure and allows to start with a smaller solution and then potentially gradually scale-up - A set-up without the need for construction of pipeline means that potentially fewer stakeholders need to be involved	- Solutions with vessels (set-up #6) and with FSU (set-up #7) are more expensive than with a pipeline from the port (set-up #8)
	# 8, #9	- Pipeline from source binds emitters, lowering competition for CO2 and providing more security (thus potentially making it easier and less expensive to find investors, especially if the pipeline entails certain CO2 sources like iron & steel industry in the Hamburg area) - Potential synergies with a planned P-t-X plant close to Esbjerg port, i.e. if the plant will need to use carbon, it could be possible to share the pipeline from emission sources and also costs	- To be fully efficient, solutions with pipeline transport from mission source require that the full-scale infrastructure is constructed from the start (i.e. it is not meant to start small and then expand/add-on later on) - Solution with pipeline form source (e.g. DE) require pre-work, i.e. collaboration and agreements with German companies and potentially state

5.4 ASSESSMENT OF DANISH COMPETITIVENESS FOR CO2 STORAGE

To assess the competitiveness of the Danish CO2 storage, criteria for competitiveness need to be defined. In this case, the following **criteria** are considered suitable **to assess the competitiveness of a CO2 storage solution**:

1. A low-cost solution: Although this report has not compared the cost of CO2 storage in different countries, it was assessed that onshore storage is the least expensive solution for CO2 storage, followed by near-shore storage and offshore storage as the most expensive option. Similarly, when large CO2 volumes are concentrated, pipeline proves to be the most cost-effective transport solution for distances of up to ~700 km. Combining offshore solution with an onshore transport pipeline (from source) can thus potentially provide a more cost-effective solution than a combination of offshore storage and CO2 transport by sea
2. Offers low marginal cost: Ability to create a solution that allows flexibility – i.e. it is possible to add or reduce volumes at a low additional cost
3. Provides high solution convenience (for other countries): A solution that is convenient for the CO2 producer; This could be geographical proximity or an easy and/or a low-cost way to push over large amounts of CO2, i.e. without investing in multiple storage facilities and complex logistics set-ups

Based on the analysis of the different **set-ups for transport and storage of CO2 in Denmark**, the following **factors** are identified in **providing Denmark with a competitive advantage**:

- Denmark can establish varying set-ups and even combine them if needed. Possible storage solutions include onshore, nearshore and offshore sites and the possibility of establishing varying transport solutions (e.g., pipelines, shuttle tanker, vessels, etc.). All storages can be potentially combined through a network of pipelines, allowing for a huge storage capacity (e.g., ~40 MtCO2/y), high input flexibility and a low total cost per tonne of CO2 (as a result of combining the least costly solutions for both storage and transport); Different solutions can also be added/expanded over time
- Denmark is strategically located close to Northern Germany, which has one of the largest CO2 sources in Europe. Close geographic proximity, combined with a possibility to build a pipeline from a cluster in Northern Germany, can provide a very cost-effective and overall convenient solution for Germany
- Likewise, Denmark is favourably located regarding CO2 transport by sea from target countries, Sweden, Finland, and Poland. Although, e.g., SE has formally announced that they are interested in collaboration with Norway for storage of CO2, many of the CO2 in both Sweden and Finland comes from the pulp and paper plants that are spread along the

coasts. As the CO_2 can be stored on the eastern side of Denmark (e.g., in Havnsø), or loaded off for pipeline transport to other storage sites in Denmark, this could potentially provide a cost-competitive solution that is also highly convenient (as large amounts of CO_2 will only need to be shipped halfway compared to storages in, e.g., UK or Norway).

Based on the above, Ramboll assesses that Denmark can offer a highly competitive solution that is cost-effective, flexible, and a convenient option for the target countries (especially Germany, Sweden, Finland and potentially Poland). The most cost-competitive solutions include set-ups where large CO_2 amounts are contracted via pipeline and those that comprise or combine onshore and nearshore storage sites.

5.5 INSTITUTIONAL CONSIDERATIONS

It is important to consider varying institutional set-ups of CCS since although CCS is technically feasible and can remove CO_2 emission on a large scale, the business case for it does not exist. Market failures prevent actors from developing CCS on their own. There are two principle market failures at work:

- The price of emitting CO_2 is lower than the socioeconomic cost of emitting CO_2. This incentivises businesses to emit CO_2 since, from a financial perspective, this is more profitable than what is logical from a socioeconomic perspective (negative externality)
- CCS technology has the characteristics of a public good, i.e., it is useful to the public/others and not only to the technology developer. The developer will thus carry the costs while the benefits are shared by the public (positive externality)

Additionally, there are investment barriers such as establishing a storage facility that comes with a high up-front cost. In contrast, the costs become lower for any new actors entering to utilise the existent set-up. They benefit from the experience and knowledge from the first developments, which will lower costs for subsequent actors who enter. Thus, from a business perspective, it can therefore be profitable to wait until the first movers have incurred the cost of early development. Finally, there is a need for many actors since the whole chain involves activities from capture, to transport and storage. This creates a risk in terms of the development and dependency of other actors; A risk that is difficult for one industry actor to take.[217]

The above highlights the inevitable need for state involvement since without it, there will be no incentives with current conditions for market actors to embark on CCS deployment alone. Further, it also stresses the importance of considering institutional set-ups. The interfaces that arise from the transition between the different CCS value chain segments leads to uncertainties and possibly complex institutional set-ups, which shall be addressed. However, suppose the institutional set-up is robust and carefully planned. In that case, CCS can be deployed at scale, and the CCS abatement cost might come down and be more favourable compared to other CO_2-reduction solutions.

To understand the need for state involvement and the interplay between different actors and institutional set-ups, it is useful to outline cases in other countries with CCS projects. Following case studies will be described below: the Norwegian full-scale carbon capture, transport and storage demonstration project "Longship", three large CCUS developments in the UK and the Government's CCS business model considerations, and the Porthos CCS project in the Netherlands. Main takeaways from the cases (regarding institutional set-ups) are presented at the end of this section.

Box 5 – A note on business case set-ups vs. business models

A pivotal distinction is made between business case set-ups and business models. Business case set-ups bring forth the most relevant market-based cases for which the profitability and break-even is calculated, whereas business models incorporate the organisational aspects; In this case, pivotal institutional considerations necessary to develop transport and storage infrastructure and operate it, which are discussed below.

[217] Natalia Romasheva and Alina Ilinova - "CCS Projects: How Regulatory Framework Influences Their Deployment"; Norwegian Ministry of Petroleum and Energy, Longship – Carbon capture and storage

5.5.1 Case studies from Norway, UK and the NL

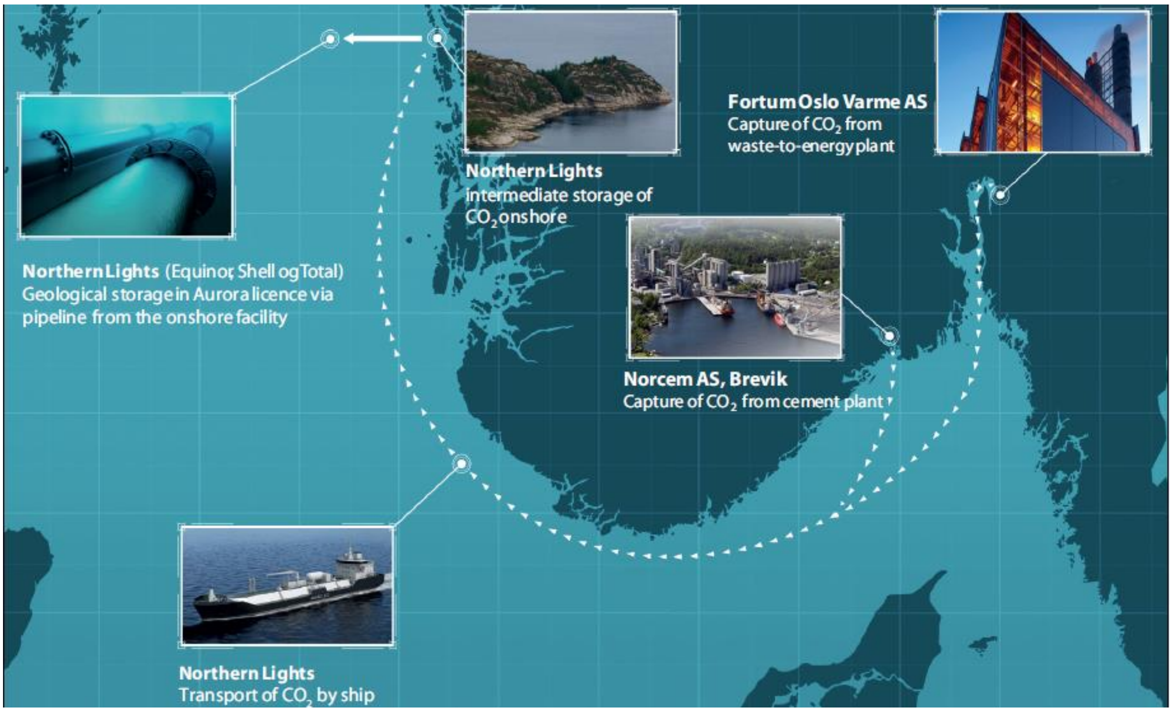
5.5.1.1 Norway: The Longship carbon capture and storage project

The Norwegian Government proposed to the Norwegian Parliament that funding be provided to establish a full-scale CCS project named "Longship". The objective of the Longship project is to demonstrate that CCS is feasible and secure and to facilitate learning and cost reductions in subsequent projects. Further, according to the white paper to the Norwegian Parliament from the Norwegian Ministry of Petroleum and Energy, *"Infrastructure will be developed with additional capacity that other projects can utilise. Hence, the threshold for establishing new carbon capture projects will be lowered. Longship can also facilitate business development through harnessing, transforming, and developing new industries in Norway"*[218].

The Longship project set-up was based on a pre-feasibility study conducted by Gassnova in 2015, which recommended that a transport and storage actor was needed to provide services to other industry actors who did not possess expertise in CO2 transport and storage. Further, the study suggested dividing the value chain into parts where each actor has responsibility for the undertaking within their activities. Meanwhile, the state would minimise the risk of these actors by acting as the intermediary between the interfaces of the value chain parts, which requires the state to ensure the value chain functions throughout the design phase to the realisation and operational phases, concerning the interfaces, schedules and operational risks.

The Longship project's key operating parties are shown in the picture below. They include the Northern Lights Consortium, which is a collaboration between Equinor, Norske Shell and Total E&P who has the role of intermediate storage onshore, transport and geological storage. Equinor has the lead responsibility of CCS studies performed by the Northern Lights. The Longship project also includes industry companies capturing CO2 at their plants, hereunder, the cement company Norcem AS (part of the HeidelbergCement Group) as well as the waste-to-energy incineration plant Fortum Oslo Varme AS**.**

Figure 14: Overview of Longship project

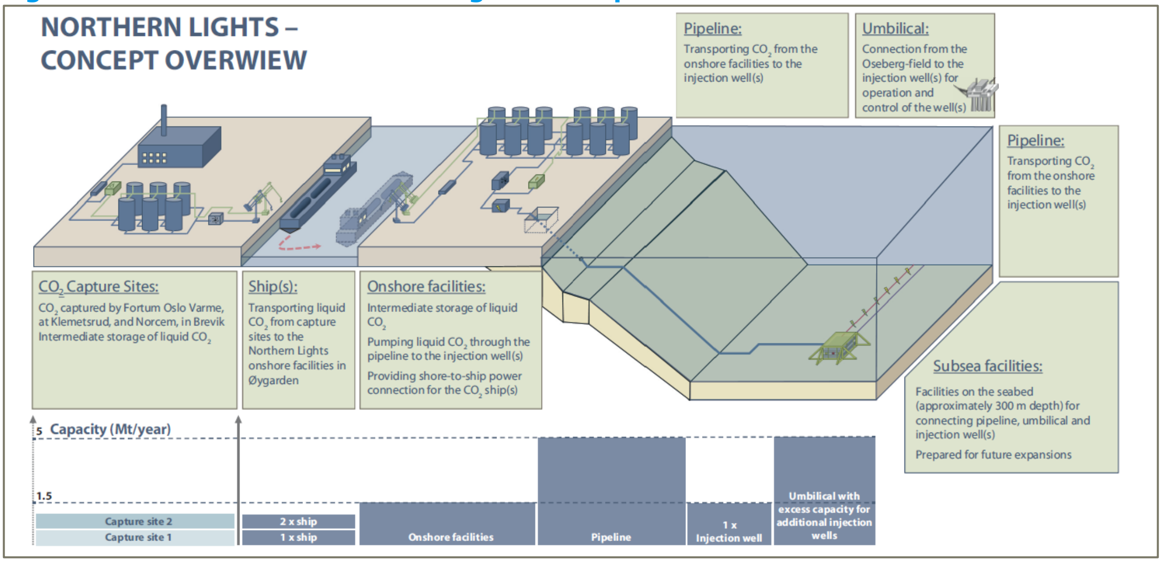


Source: Norwegian Ministry of Petroleum and Energy, Longship – Carbon capture and storage

The Northern Lights Consortium's concept is shown in the below picture and is an integrated part of the Longship project.

[218] Norwegian Ministry of Petroleum and Energy, Longship – Carbon capture and storage, p. 7

Figure 15: Overview of Northern Lights concept



Source: Norwegian Ministry of Petroleum and Energy, Longship – Carbon capture and storage

In addition to the key stakeholders involved in the operation of the Longship CCS project, the institutional set-up of the project importantly also includes the Norwegian Government, the Norwegian state and Gassnova, who is the state enterprise for CCS made up of members from Gassnova and the Norwegian Ministry of Energy and Petroleum. The role of all the parties in the institutional setup is described below.

- The Norwegian Government brought forth to the Norwegian Parliament that funding should be allocated for the implementation of the Longship project. The Government continues to foster international cooperation on technology development and emission reduction, which are key to Longship. They also have the role to follow up on the Longship project and the benefit realisation work in close collaboration with the industrial companies and share the learnings of CCS in Europe and the world.
- The Norwegian state acts as the intermediary between Norcem, Fortum Oslo Varme (if applicable) and Northern Lights. The state carries risks related to the interfaces between the different parts of the project, as well as the risk associated with project scheduling and costs. The state will need to balance the risks with the costs since costs will need to be kept at a minimum to demonstrate the project feasibility and a successful effect of the project. The state is expected to cover about two thirds (NOK 16.8 billion of 25.1 billion) of the project costs. However, the state's eventual costs will depend on the actual costs of the project. The costs are high, and the state carries risk through funding agreements with the industrial companies. The state will not engage in negotiations of state aid with individual stakeholders. Uncertainty also prevails beyond the state's control that affects the project success, such as other countries' climate policy development and the number of subsequent projects implemented
- Gassnova leads the overall planning of Longship; Follows up on the actors' project management through agreed reporting on behalf of the state, and manages the study contracts with the industry partners. Gassnova evaluated the FEED studies and subsequently provided project recommendations to the Government[219]. Gassnova also coordinates the work on benefit realisation and facilitates the sharing of relevant experience with other projects and stakeholders to ensure the overall project goals are met.
- Equinor – the majority of which is state-owned –formed a consortium with Norske Shell and Total E&P, named Northern Lights**.** Equinor also has the lead responsibility of carrying studies of CO2 transport in connection to the Longship project. They are jointly responsible for the CO2 transport and storage part of the project. Knowledge and

[219] In the Fall of 2016, Gassnova announced two competitions for state aid to carry out concept selection and front-end engineering design (FEED) studies; one for CO2 capture on industrial sites and one for geological storage of CO2. After the studies were completed the Storting pledged funding to initiate the FEED studies at Norcem and Fortum Oslo Varme.

experience from the Petroleum industry have been and are vital to the CCS development in Norway. The companies will own and develop the project, which comprises shuttle tankers for transport of liquid CO2, a reception terminal in Øygarden municipality located in Vestland county on the south-west coast of Norway, and pipeline to a well where CO2 will be injected into a storage formation beneath the seabed. The state aid agreement for the transport and storage part of the project has been designed to regulate the cost and the risk distribution of the project, including incentives to keep costs low and bring in new projects. All of the Northern Lights' revenues will stem from CO2 storage from recent projects. Thus, Northern Lights has a solid incentive to develop the market for CO2 storage. Further, the Ministry of Petroleum and Energy considers it pivotal that Northern Lights' capacity is utilised by industry actors not financed directly by the Norwegian state. The success of this will provide evident proof that the project has the desired effect. Northern Lights has also contributed to the benefit realisation work during the FEED phase. Northern Lights comprises a two-phase development plan: The first phase includes an estimated capacity of 1.5 MtCO2/y (completed mid-2024) over 25 years. A subsequent and potential second phase is estimated with a capacity of 5 MtCO2/y.

- Norcem is a Norwegian cement manufacturer part of the Heidelberg Cement Group, where carbon capture from its activities at its factory in Brevik is performed. The company conducted FEED studies and has also verified their selected carbon capture technologies, optimised integration, prepared contracts with key suppliers and prepared benefit realisation plans. The Norcem capture development has a large state grant (NOK 3.8 billion)
- Fortum Oslo Varme is a waste incineration plant, and carbon capture from its activities at the waste incineration facility at Klemetsrud, Oslo is performed. The company conducted FEED studies and has also verified their selected carbon capture technologies, optimised integration, prepared contracts with key suppliers and prepared benefit realisation plans. However, the Ministry of Petroleum and Energy ranks Norcem significantly higher than Fortum Oslo Varme since the state's costs and risks are lower for Norcem's project than Fortum Oslo Varme's project. The state aid is limited to NOK 2 billion in investments and NOK 1 billion in operating expenses and the rest of the costs Fortum will need to apply for external funding. Thus, the Fortum Oslo Varme project is dependent on external funding for it to become operational and has therefore applied for a large grant via the EU innovation fund

The Longship project highlights the importance of state involvement to a large extent, since not only is the state itself involved combined with Government support, but Gassnova and Equinor are both state-owned organisations. Gassnova ensures that the state's interests are incorporated throughout the project, whereas any substantial revenue gains made by Equinor is state-owned and thus also controlled.

5.5.1.2 UK: CCUS developments and the Government's CCS business model propositions

The UK Government has recently funded three large developments that will jointly deliver CCUS applications to approximately 50% of the industrial emissions generated in the UK: Teesside (NZT) and Humber projects (ZCH) which will be connected by the Northern Endurance Partnership (NEP).[220]These developments are a consequence of the UK's Ten Point Plan, which outlines the need and ambition to develop a CCUS industry.[221]

The below picture shows the connection between the three developments in the UK.

[220] Business Live – "Huge North Sea carbon storage solution backed alongside the regional projects set to feed it"

[221] HM Government – "The Ten Point Plan for a Green Industrial Revolution"

Figure 16: Overview of the three large development projects delivering CCUS solutions in the UK

Source: Oil and gas climate initiative

The NZT is a full chain CCUS project led by oil and gas majors **B**P, Eni, Equinor, Shell, and Total, with BP as the main operator. From 2025, the project aims to capture up to 10 mtCO2 emissions per year.

The ZCH is a partnership that will build a net-zero industrial cluster and has the ambition to decarbonise the North of England, including solutions such as low carbon hydrogen production, CCUS and shared onshore and offshore infrastructure and greenhouse gas removal technology. It comprises 12 formal partners**:**

- Associated British Ports (UK's leading port operator),
- British Steel (steel producer),
- Centrica Storage (Gas facilities),
- Drax (UK's third-largest electricity generator),
- Equinor (Oil and gas),
- Mitsubishi power (power generation equipment),
- National Grid Ventures (developing and operating energy infrastructure),
- PX Group (manages, operates, and maintains industrial facilities),
- SSE Thermal (developer, owner and operator of electricity generation and energy storage assets),
- Triton Power (power generation),
- Uniper (energy company) and
- The University of Sheffield AMRC (network of world-leading research and innovation centres working with manufacturing companies)

By 2026, ZCH expects to capture at least 17 MtCO2/y from projects across the Humber 2035.

The NEP will develop the offshore infrastructure to transport and store millions of tonnes of CO2 in the UK North Sea. BP, Eni, Equinor, National Grid, Shell and Total formed the NEP Partnership, with BP as the operator.

All three developments have secured funding from the Industrial Strategy Challenge Fund, which the UK Government sets up to address the most significant industrial and societal challenges using research and development based in the UK. Jointly the three developments have received GBP 229 million in public and private funding. Thus, as was the case with the Norwegian Longship project state funding, is once again proven to be key to mobilise CCUS projects and further unlock private investments.

Further, the UK Government has published a whitepaper on potential business models for CCUS in which the Government indicates which ones they find most promising:

- CO2 transport and storage**:** a regulated T&S network where financing follows a RAB business model[222], in which there is an economic and market regulator, and the risks are allocated to those who are best able to manage them.
- Power CCUS: a payment model with payment availability of low carbon generation capacity (providing a known return of investment payment for investors)[223], and a variable payment (to account for a power CCUS plant's added costs, relative to those of an equivalent unabated plant). This payment combination could allow a plant to operate flexibly, provide value to a low carbon electricity system with increasing renewable capacity, and yet provide certainty to investors.
- Industrial CCUS**:** a hybrid model comprising three phases. Phase one entails an industrial contract for difference (CfD) with upfront capital support to assist with revenue support for a set duration, and CfD payments would cover the operating cost of capture, recovery of the CAPEX investment made by the owner of the plant, and costs for accessing the CO2 T&S infrastructure. Phase two entails a transition to competitively allocated CfD after the risks and costs are reduced in phase one, whilst upfront investment funding from the Government is phased out. Phase 3 is a market-based approach, where CCUS is sustained by the CO2 price alone, based on the assumption that as the market matures, costs of CCUS technologies will come down, and pass-through costs will increase with a more developed market for low-carbon industrial products along with policies allowing efficient competition.

Together with the CCS Infrastructure Fund, the business models shall incentivise decarbonisation and cost reductions while minimising the risk of market distortions. The Government recognises the inherent market failures and emphasises the need for their involvement, primarily to support the value chain interfaces and fund the initial clusters to help unlock capital investments. However, it is important the financing model reflects the large upfront capital investments and that the operational costs are expected to be lower, and thus supports investment and returns across the asset's lifetime.

The UK Government's preferred model for CO2 transport and storage is further elaborated upon below to highlight the importance of state involvement both in terms of funding but also in terms of financial regulatory oversight and the need for risk allocation in order for the CCS market to function efficiently. The CO2 transport and storage model shall incorporate the following pivotal aspects:

- The Government supports and incentivises the investment in CO2 infrastructure, especially for the first developments
- CO2 transport and storage regulated by an independent body to oversee the industry and deploy Government policies to address natural monopolies issues linked to regional T&S networks
- Finance and funding through a RAB model[222] consisting of regulated revenue streams determined by a building block approach (representing a category of costs incurred by the project company, which are scrutinised by the economic regulator to ensure costs are efficient) paid by the users of the T&S network determined by an economic regulator to mimic the incentives similar in a competitive market. The economic regulator and market regulator would oversee the interface of capture plants to the T&S network, similar to the Oil & Gas Authority's role in awarding CO2 storage licenses offshore. This role could be performed by a single entity
- T&S risk shall be allocated to the party that is best able to manage them, however, no risk model has been developed. The Government will work with the CCUS T&S Expert Group to develop an understanding of the risks[224]

[222] RAB is short for Regulated Asset Base: "The T&S company would receive a licence from an economic regulator, which grants it the right to charge a regulated price to users in exchange for delivering and operating the T&S network. To prevent monopolistic disadvantages, the charge is set by an independent regulator who considers allowable expenses, over a set period of time, to ensure costs are necessary and reasonable. Model variants could include the provision of financial support to decrease the upfront capital expenditure.", p 21. Source: UK, Department for Business, Energy & Industrial Strategy – "A Government Response on potential business models for Carbon Capture, Usage and Storage"

[223] The availability payment could be a stable ongoing payment from a counterparty to the generator. This could be paid based on the availability of low carbon generation plant, could be set relative to the cost of the generation and capture plant, taking into account capture rate availability, and could be indexed to inflation.

[224] UK, Department for Business, Energy & Industrial Strategy – "A Government Response on potential business models for Carbon Capture, Usage and Storage"

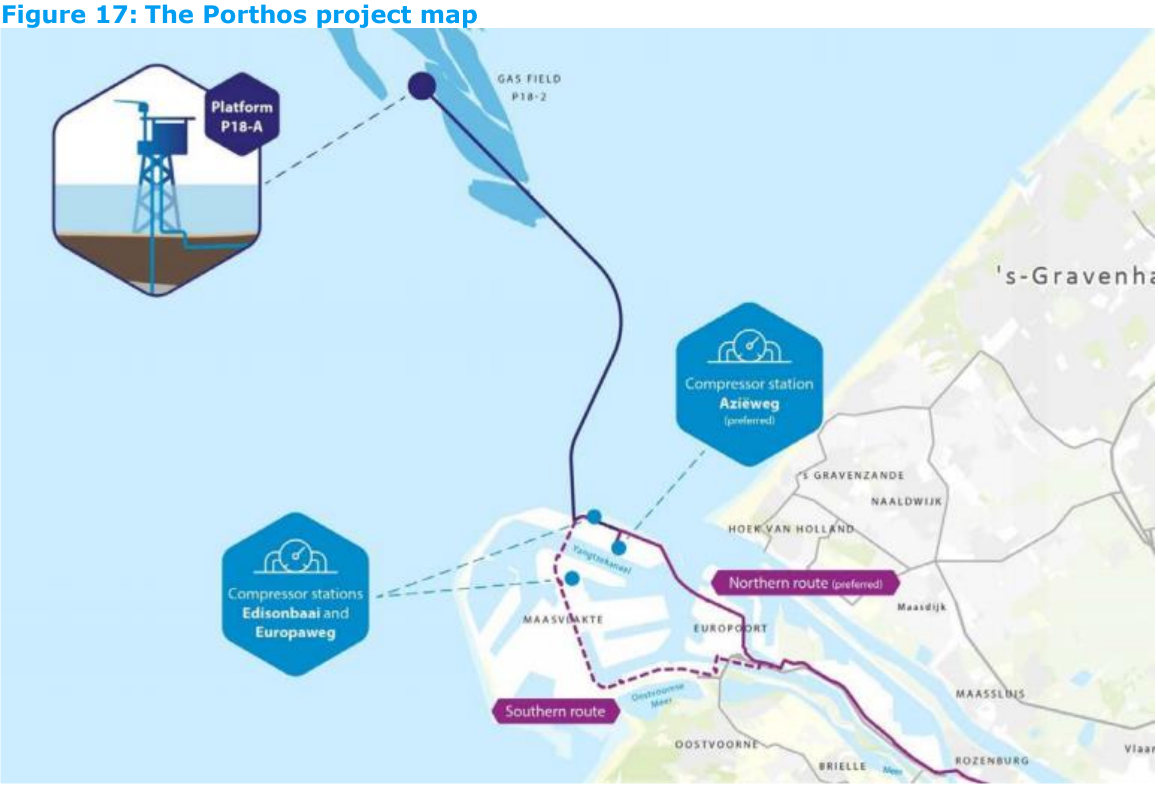
The UK Government's whitepaper on CCUS business models illustrates not only the need for state funding. Still, it emphasises the need for the Government to propose and establish business models and act as the intermediary as with the Longship case.

5.5.1.3 The Netherlands: The Porthos project

Porthos[225] CCS project is developed in the Netherlands to transport CO2 from industrial activities in the Port of Rotterdam and store the emissions in empty gas fields (P18-2, P18-4 and P18-6) below the North Sea. Over 15% of the Netherland's CO2 emissions are emitted in the Rotterdam Port area. Various industry companies will capture the CO2, and they will supply it to an existing pipeline that runs through the Rotterdam port area and is approximately 30 km. The CO2 will then be transported through a 19 km-long offshore pipeline to a platform laid beneath the North Sea, approximately 20-25 km off the coast. The project infrastructure is proposed to be developed as "open access" to capture, transport and store CO2 from industry companies in the Port of Rotterdam, such as refineries, chemical producers, and hydrogen plants. Companies will be subject to pay a fee for having their carbon emissions transported and stored by the Porthos. It is expected that the project will be operational from 2024, and during the first years, it is estimated that 2.5 MtCO2 can be stored per year[226].

The Porthos project is mapped below.

Figure 17: The Porthos project map



Source: Porthos CO2 transport and storage website

The key stakeholders in the project are the following three main parties:

- The joint venture amongst the Port of Rotterdam Authority, Gasunie and EBN, who are all state-owned and will be responsible for the transport and storage of CO2. The Port of Rotterdam Authority contributes to the project with its experience and expertise in the local situation and market, Gasuine has experience and knowledge within gas infrastructure and transport, and EBN contributes with its expertise within offshore infrastructure and has expertise within the field of deeper soil layers
- parties contribute the following
- The Dutch government who provides funding and mandate

[225] Porthos stands for Port of Rotterdam CO_2 Transport Hub and Offshore Storage.

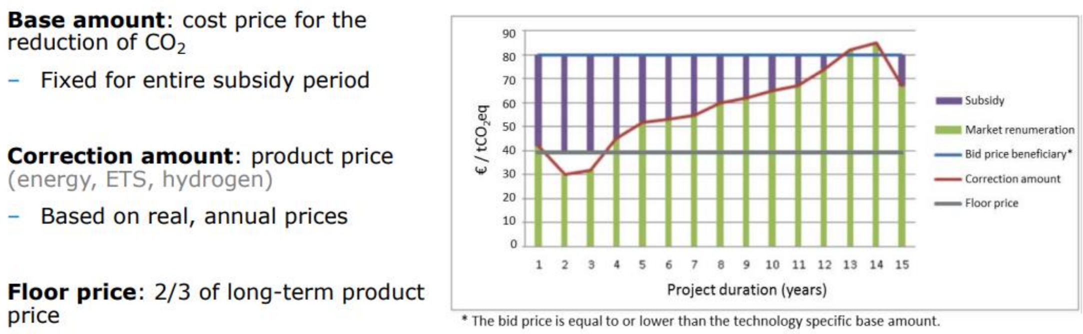
[226] Porthos CO2 transport and storage website

- Private companies that will supply CO2 invest in carbon capture and pay for storage.:

The joint venture wanted to build the infrastructure, and to build it, they needed private companies to commit as clients, however, while the clients also wanted the infrastructure, they needed funding for capture infrastructure and storage fees. Meanwhile, the Dutch Government wanted to ensure the infrastructure before providing funding to the private companies[227]. The solution to this was to establish agreements with both the Government and companies supplying CO2. Thus, so-called Joint Development Agreements (JDAs) has been signed between Porthos and four companies: Air Liquide, Air Products, ExxonMobil and Shell, although the agreements are not binding. The JDAs underlie that Porthos and the companies collectively work towards definite transport and storage contracts[228].

An important development to enable these companies and others to make investments within decarbonisation has been the Dutch sustainable energy transition subsidy scheme (SDE++), which was updated in 2020 from SDE+ to SDE++ to broaden the scope and provide funding for CCS projects and other decarbonisation technologies. In 2021, the four private companies: Air Liquide, Air Products, ExxonMobil and Shell, applied for EUR 2 billion from SDE++, which is expected to be granted in the spring of 2022.[229] The SDE++ also provides funding for transport and storage infrastructure. The subsidy scheme builds on a CO2 premium, which is based on the cost (CAPEX and OPEX over a 15-year period) and revenues, as per the existent ETS scheme. The SDE++ only provides a subsidy for the profitable part of the project (see the illustrative graph of this), and the subsidy is adjusted on a yearly basis based on the ETS price. Since CCS is viewed as a relatively complex technology, the subsidy rounds are conducted on an open book basis. Receivers of the subsidy must report the costs incurred to avoid over subsidy. They are also subject to completing feasibility studies, and the projects must be realised within a 5-year period. The SDE++ funds the most competitive technologies, and the estimated costs of applications are calculated by the Dutch Environment Agency, which provides a maximum subsidy. For CCS, the maximum is EUR 62 per tCO2, but it can exceed EUR 100 per tCO2 depending on the project (e.g., considering capture methods for hydrogen production in terms of methane).[230]

Figure 18: The SDE++ provides subsidy only for the profitable part of the project



Source: Porthos CO2 transport and storage website

Funding for Porthos has also been collected from several other sources; for the feasibility studies, Porthos was granted EUR 1.2 million from RVO (Netherlands Enterprise Agency) in 2018 and EUR 6.5 million from the European Commission in 2019, as well as a subsidy of EUR 102 million from Brussels for the construction of the infrastructure in 2021. In 2020, Porthos was deemed a "Project of Common Interest (PCI)" by the EU, which are cross border infrastructure projects deemed pivotal and they link energy systems of EU countries.

The final investment decision is expected in 2022. It is dependent on technical development infrastructure, Environmental Impact Assessment and permits, the securing of agreements with

[227] The Dutch Ministry of Economic Affairs & Climate Policy: Clean Energy Solutions Center – "Carbon Capture, Utilization and Storage in The Netherlands (Webinar)"

[228] Porthos CO2 transport and storage website

[229] Offshore Energy website –" Porthos CCS project: Industry targets €2 billion in Dutch subsidies"

[230] The Dutch Ministry of Economic Affairs & Climate Policy: Clean Energy Solutions Center – "Carbon Capture, Utilization and Storage in The Netherlands (Webinar)"

companies to supply CO_2, as well as the Dutch government's continued support to enable CCUS. After the final investment decision, the construction of the project can be initiated.[226]

The Porthos case outlines once again strong representation from state-owned entities, Government intervention, especially to get the project started and to incentivise and enable the private companies to commit to CCS ventures. Further, this case also importantly portrays European funding to support site preparations.

5.5.2 Lessons learnt

There are three main takeaways from the cases presented above regarding institutional set-ups:

1. The necessity of state involvement in terms of funding (upfront capital expenditure), risk management and supporting the initiatives
2. The need for a body that acts on behalf of the state and administers and maintains the strategic overview of the project progress and follow-up
3. The need for parties who possess operational and technical expertise

All three country cases highlight the importance of state involvement since other actors do not have the capacity or economic incentive at present to drive the development for CCS on their own. Thus, there is most likely a need for state-aid and state involvement in Denmark as well, and the Danish Government will probably need to take a supportive role in the CCS initiative.

Further, the cases illustrate the need for an organisation to take the overall lead and oversight role; One that will act on behalf of the state to ensure the project is progressing accordingly and that the incentive structures that are in place are working efficiently to demonstrate market-based success, e.g., in the Longship case this role is held by Gassnova. To this, a possible existent candidate could be the Danish North Sea Fund ("Nordsøfonden"), Energinet or its subsidiary Gas storage Denmark to take on this lead administrative and oversight role of CCS in a Danish context. Another candidate to take on this role is the Danish Energy Agency. Alternatively, a new entity might need to be established. It is also important to consider that the candidate covering this role has the necessary expertise in the varying set-ups between onshore, nearshore, offshore or a combination of these.

Additionally, an entity or a group of entities representing the state to some extent in the operational role of CO_2 transport and storage has also been identified in all cases. In Longship, Equinor (state-owned) has the lead role of operating and overseeing the transportation and storage of CO_2, whereas, in Porthos, this role is held by three companies in a joint venture who are all state-owned. Similarly, the regulated T&S network business model that the UK Government is favouring is also comprising a state-economic regulatory body that can oversee transport and storage interfaces of CO_2. In Denmark, there is a limited number of companies that are state-owned and would be suitable for this role. However, one candidate could be Energinet or its subsidiary Gas storage Denmark might be candidates to take this responsibility. However, these entities do not encompass offshore geological knowledge, so they would be more suitable in a business model set-up comprising an onshore and possibly nearshore solution. In an offshore set-up, this transport and storage operating role could also be a constellation comprising oil and gas companies (e.g., Ineos, Total) underlying a model where there is a competition to ensure costs are kept efficient, and revenues are allocated.

The cases also portray the importance of involving parties with technical knowledge about geological storage, capture technology etc. Additionally, as EBN in the Porthos case possesses knowledge about deeper soil levels, it can be necessary to involve this type of organisation in the institutional set-up in Denmark (e.g. GEUS that has geological expertise).

It is essential to consider an appropriate institutional setup to incentivise the deployment of CCS projects and to plan a constellation of value chain partners who can work seamlessly between the interfaces of the value chain segments. It is also pivotal to tailor the institutional set-up so it fits the chosen project location and infrastructure set-up (e.g., offshore, onshore, nearshore or a hybrid of these) since the entities will need to possess expertise suitable to this.

6. PROFITABILITY ASSESSMENT OF CO2 STORAGE IN DENMARK

6.1 INTRODUCTION TO BUSINESS CASES

The business cases in this chapter are developed to assess the return on investment of different feasible set-ups for the transport and storage of CO2 in Denmark. An important distinction is made between the business case set-ups and the business models. Business case set-ups bring forth the most relevant market-based cases for which the profitability and break-even are calculated, whereas business models incorporate the organisational aspects; In this case, pivotal institutional considerations necessary to develop CCS infrastructure and operate it. This chapter outlines the selected business case set-ups.

Box 6 – A note on the business cases' profitability and underlying revenue

It is important to clearly state that all business cases assume state-aid in order to become profitable. The reference price applied underlies state-aid, i.e. the price will be a combination of e.g., CO2 prices, CO2 taxes, grants etc. Without these support mechanisms the CCS business cases will neither result in the net present values (NPV) nor the payback periods presented.

It is difficult to estimate a precise price for CO2 transport and storage since the market is immature and there exists no defined market price at present. CO2 prices and subsidies are potential ways to construct the price, however, it is highly uncertain to what extent, who and how these will be allocated in the future (e.g., income from CO2 pricing will also cover other technologies than CCS). Thus, we have instead developed an alternative reference price, which is based on a feasible competing set-up in the countries that are the main competitors to Denmark: UK and Norway.

Based on the assessment of Denmark's competitive traits in section 1 three overarching business cases are presented:

Case 1): Small-scale - Denmark to become a domestic CO2 storage provider purely with sea transportation only

This case is purely focused on the national market of CO2 transport and storage. Denmark will store 5 MtCO2 from domestically sourced CO2 volumes at an offshore storage site in the Northern fields, to which 3 Mt will be shipped with vessels from Copenhagen and 2 Mt from Aalborg. In practice, CO2 can be picked up by vessels from any location, also from abroad and also depending on market supply. However, this case assumed only Danish CO2 for the business case calculations.

This case is appropriate if the intention is to have more flexibility and establish a starting point for CO2 transport and storage in Denmark. This case can offer more flexibility in that it provides a platform to get started with CO2 transport and storage while it does not necessarily limit the option to expand the infrastructure later. However, it could limit Denmark's unique opportunity to offer CO2 storage internationally and take on a leading CO2 storage provider role, which might be difficult to claim later when competing countries have developed their infrastructure. Moreover, since this case takes a point of departure in vessel transport as well as offshore storage, it is the most expensive case in terms of cost per ton of CO2 (particularly demonstrated by the need for higher operational expenditures due to a higher number of wellhead platforms, standby vessels as well as mooring and loading systems required).

Note that small-scale cases could also be developed for onshore and nearshore storage, and these solutions could potentially have similar advantages and lower costs than the offshore solution in case 1. However, the scope of this report only comprises the offshore storage for the small-scale solution.

Case 2): Medium-scale - Denmark to become a domestic CO2 storage provider primarily while serving the international market to some extent

In this case, Denmark is storing CO2 for 10 MtCO2/y and will still focus primarily on storing domestic CO2 volumes; 5 MtCO2/y will be reserved for Danish CO2 volumes (3 MtCO2/y from Copenhagen and 2 MtCO2/y from Aalborg), while also providing 5 Mt storage capacity for CO2 volumes coming from Germany, Sweden, Finland, Poland and/or the Netherlands. As such, the primary focus will be to serve the national market while also entering the international market at some scale.

This provides a starting point for becoming an internationally claimed player within CO2 transport and storage in Northern Europe. This case is suitable if the intention is to enter the international market from the beginning and take on less risk and limit the up-front capital investments than comparing to case 3 (large-scale international CCS solution). All of the options, in this case, have a lower cost per ton of CO2 than case 1 while being higher than case 3. Further, the options, in this case, provides the opportunity to expand the CO2 transport and storage later. However, as with case 1, these options limit Denmark's possibilities to offer CO2 storage internationally on a large scale and take on a leading CO2 storage provider role, which might be challenging to claim later when competing countries have developed their infrastructure. Additionally, while the solutions in case 2 require less complexity and investments in CCS infrastructure than case 3, they will also result in a smaller number of market players. Thus, there is less competition and potential for the case to become more market-oriented.

There are three different storage placement options for this case:

2A) Onshore CO2 storage,
2B) Nearshore CO2 storage, and
2C) Offshore CO2 storage

The onshore CO2 storage scenario includes a planned 10 MtCO2/y storage in Havnsø with a pipeline from Copenhagen to Kalundborg and shuttle tanker transport to Havnsø harbour from international countries. As previously demonstrated, the onshore possibility is the most affordable option, and thus, Denmark can provide a cost-effective solution for potential export countries. However, there might be some public opposition since there are housing areas onshore (and the general opposition against onshore storage observed in some other countries).

The nearshore option includes a planned 10 MtCO2/y storage in Hanstholm about 50 km from shore, a pipeline from Copenhagen to Hanstholm (partly onshore and partly offshore, via Fredericia), one onshore pipeline from Aalborg to Hanstholm and one shorter, offshore pipeline from Hanstholm port to the storage site. Furthermore, shuttle tanker transport is assumed to Hanstholm harbour from international countries. This scenario is more expensive than the onshore scenario yet less expensive than the offshore scenario.

The offshore scenario includes a CO2 storage site in the North Sea fields with a planned capacity of 10 MtCO2/y, a pipeline from Copenhagen to Esbjerg (partly onshore and partly offshore, via Fredericia), as well as shuttle tanker transport to Esbjerg harbour from international countries. CO2 is then transported from Esbjerg to the offshore site via an offshore pipeline (the case assumes reuse of the existing gas pipeline). This scenario is more expensive than 2A and 2B. Furthermore, for many of the source countries, the distance to this storage by ship is not significantly different from the offshore storage possibilities that UK or Norway is providing. Thus, there will be a potentially lower incentive for export countries to opt for storing their CO2 in Danish offshore storage comparing to Norwegian storages or even CO2 storages provided by the UK, compared to the onshore and nearshore solutions.

Case 3): Large-scale - Denmark to become an established large-scale international CO2 storage provider while serving the domestic market simultaneously

In this case, Denmark is a large-scale CO2 storage provider for international markets. Denmark has a competitive advantage in terms of its location, as Denmark is strategically located in close proximity to Germany – the largest CO2 emitter in Europe and Sweden, Finland, Poland, and The Netherlands. Denmark can provide an attractive and cost-effective pipeline solution for German CO2 volumes, a pipeline spanning from Northern Germany to Esbjerg serving 20 MtCO2/y. In total, Denmark will store 40 MtCO2/y; 20 MtCO2/y from Germany; 15 MtCO2/y in total from Sweden, Finland and Poland, as well as 5 MtCO2/y domestically from Denmark. In this case, the Netherlands is not accounted for since the case will mainly focus on serving pipeline and shipping solutions for Germany and the countries located East of Denmark. However, this option does not exclude any potential CO2 volumes coming from the Netherlands, e.g. by ships, and these volumes would be considered as an additional upside.

This case includes storages in Havnsø (10 MtCO2/y), Hanstholm (10 MtCO2/y) and two offshore storages in the Northern fields (20 MtCO2/y in total). It would also include a pipeline from

Copenhagen to Esbjerg (partly onshore and partly offshore, via Fredericia), Hamburg to Esbjerg, Esbjerg to Hanstholm, and from Hanstholm to Aalborg, one shorter offshore pipeline from Hanstholm port to the Hanstholm site and two offshore pipelines from Esbjerg to the offshore sites (the case assumes reuse of the existing gas pipeline in one case).

The advantage of this case is that Denmark will take on a leading CO2 storage provider role in Europe by providing a unique CCS solution, which the other countries do not have the capacity or possibility to offer. It will also commit Germany to store its CO2 volumes in Denmark through a convenient and cost-efficient pipeline solution. Further, Denmark will make it favourable for Sweden and Finland to store their CO2 in Denmark – by providing a pipeline connection from Kalundborg to a mix of onshore, nearshore and offshore CO2 storage sites. This would make it considerably more convenient for these countries to store CO2 in Denmark instead of shipping it to the UK or Norway.

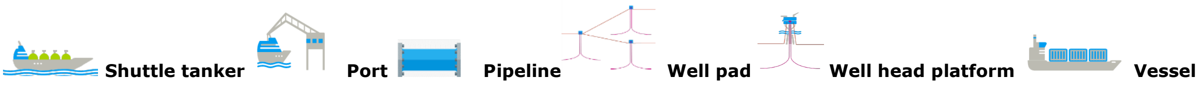
This case will also entail that various public and private bodies are involved and are responsible for different parts of the value chain. Since there are so many transport infrastructures laid out, it might involve more competition between players, and as such, CCS might become more market-oriented.

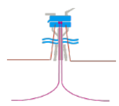
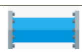
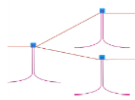
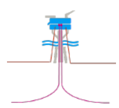
The potential disadvantages are that this solution will require extensive state involvement and investments in widespread CCS infrastructure. It will also require the EU to cooperate to support and pass policies that will aid the CCS market.

6.2 OVERVIEW OF ANALYSED BUSINESS MODELS

The scope of the business cases comprises the nationally focused business case 1 and the overarching nationally and partly internationally focused business cases 2A, 2B, 2C and the internationally-focused business case 3:

Table 46: Overview of business cases 1, 2A, 2B, 2C and 3



Case	Storage type	Potential site name (and capacity)	Assumed max. injection capacity/ year	CO2 Transport from source	Intermediate storage and preparation facilities	Transport from intermediate storage to well	Injection site
1	**Offshore**	Depleted oil and gas field in the North Sea (estimated ~2,000 Mt)	**10 MtCO2**				
2A	**Onshore**	Havnsø (927 Mt)	**10 MtCO2**	  From DK/CPH			
2B	**Nearshore**	Hanstholm (2,753 Mt)	**10 MtCO2**	  From DK/CPH			
2C	**Offshore**	Depleted oil and gas field in the North	**10 MtCO2**				

		Sea (estimated ~2,000 Mt)		From DK/CPH			
3	**Onshore**	Havnsø (927 Mt)	**10 MtCO2**	From DK/CPH	(Kalundborg)		
	Offshore	Depleted oil and gas field in the North Sea (estimated ~2,000 Mt)	**10 MtCO2**	From DK/ Kalundborg From DE/ Hamburg	(Esbjerg)		
	Nearshore	Hanstholm (2,753 Mt)	**10 MtCO2**	From DK/Esbjerg	(Hanstholm)		
	Onshore	Gassum (630 Mt)	**5 MtCO2**	From DK/Esbjerg	(Aalborg)		

Note: Shuttle tankers are considered pure transport vehicles, meaning they do not have cooling equipment and storage preparation equipment needed to connect directly to an injection site. As a result, shuttle tankers need to unload CO2 into intermediate storage near refrigeration and storage preparation equipment before it can be transferred to an injection site; Vessels can be used for transport and carry cooling and storage preparation equipment. This means they can connect directly to injection sites; Permanently moored FSU stations are considered stationary and cannot be moved. Shuttle tankers will transport CO2 to the station, which will prepare the CO2 for storage before sending it to the injection site;
Source: Ramboll analysis

Box 7 – A note on specific storage locations

All storage and transport set-ups presented in this chapter are potential illustrative scenarios only. This also pertains to the suggested storage and pipeline locations as well as the shipping routes. Thus, the business cases are not to be regarded as definitive rather as potential suggestions for feasible scenarios.

6.3 BUSINESS CASE ASSUMPTIONS

The below table summarises the assumptions applied in all four business cases. It is important to note that all individual costs inputs, i.e. transportation and storage costs presented in this chapter and utilised in the business cases, are not levelized costs.

Table 47: Input assumptions[231]

Data input	Description	Assumptions comments
Alternative reference price	Revenue	It is difficult to estimate a precise price for CO2 transport and storage since the market is immature, and there exists no defined market price at present. CO2 prices and subsidies are potential ways to construct the price, however, it is highly uncertain to what extent, who and how these will be allocated in the future (e.g. income from CO2 pricing will also cover other technologies than CCS). Thus, we have instead developed an alternative reference price based on a feasible competing set-up in the countries that are the main competitors to Denmark: UK and Norway. Nevertheless, the alternative reference price underlies state-aid, e.g., CO2 prices, CO2-taxes, grants etc., the constellation of them is not known in developing the alternative reference price. Both UK and Norway are developing CCS offshore storage sites solely, so a reference price reflecting this type of storage is appropriate. Further, applying a transport cost for a shipping distance to a location in these countries would also reflect a ballpark estimate of the transportation costs. The below explains the price in more detail.

[231] Ramboll experts

		The reference price used in this case has been based on the average cost of the Danish offshore storage site since the competing alternatives in both the UK and Norway are offshore options and, thus, considered direct competitors and alternatives to the Danish storages. Further, Edinburgh (Scotland) has been chosen as a reference storage location since it is considered a feasible direct alternative for countries exporting CO2 in Europe. Thus, the reference price also includes the shipping cost of transporting CO2 from the emitting countries (Germany, Sweden, Finland, Poland, Denmark and the Netherlands) to Edinburgh; The distances and volumes from each country are adjusted accordingly, and a weighted average of these is calculated. The price has also been discounted according to the 30-year technical lifetime. The price estimate applied is subject to uncertainty, as the CCS market is in its early stages, and the cost of CCS infrastructure is subject to technology developments and a learning curve. However, the chosen methodology is deemed most reliable for the reasons stated above, compared to alternative methods.
CO2 volume	Revenue	The volumes for each business case are based on the expected volumes coming from both domestic CO2 streams and international CO2 streams in each business case. Case 1 assumes 5 MtCO2/y, and cases 2A, 2B and 2C, as demonstrated previously, all assume 10 MtCO2/y, whereas case 3 assumes 40 MtCO2/y.
Storage	CAPEX	Storage CAPEX is based on 5 MtCO2/y for case 1, while this is 10 MtCO2/y capacity for business cases 2A, 2B and 2C. For business case 3, this is assumed to be 40 MtCO2/y, in which costs for business model set-up 2, 4 and 5 have been combined. The storage CAPEX comprises storage pre-FID costs (final investment decision), Storage instalment costs[232] and in the final year of the storage plant's lifetime (year 30), storage abandonment costs (ABEX) and storage post-closure costs are applied. ABEX is assumed to be 17.5% of total storage instalment costs.
	OPEX	The operational expenditures for case 1 storage comprise the base organisation, injection plant, injection wells, monitoring, power, wellhead platform, standby vessel as well as mooring and loading system for storage capacity of 5 Mt. Business case 2A has the same OPEX storage costs as set-up 2 for 10 Mt storage capacity (see chapter 5); Base organisation, intermediate storage, injection plant, injection wells as well as monitoring and power. Business case 2B has similar OPEX storage costs as set-up 4; Base organisation, intermediate storage, injection plant, injection wells, monitoring, power and wellhead platform. While business case 2C has the same OPEX storage as set-up 8; Base organisation, intermediate storage, injection plant, injection wells, monitoring, power and wellhead platform. Business case 3 storage OPEX is calculated based on costs combined from set-up 2 (one for storage capacity of 5 Mt and one for storage capacity of 10 Mt), set-up 4 and set-up 5.
Pipeline	CAPEX	Pipeline CAPEX comprises the cost of constructing pipelines and the number of pumping stations needed to transport the CO2 volumes. Pipeline cost varies depending on the length and rated capacity. Pumping stations are placed every 200 km for onshore pipelines and at both ends of offshore pipelines, independent of length. Regarding case 1, 2C and case 3, we are reusing the existent gas pipeline, and thus, costs for these are assessed to be zero. However, since the pipeline starts in Nybro (a short distance from Esbjerg), a new short, onshore pipeline will transport the aggregated CO2 from Esbjerg port to Nybro.
	OPEX	Pipeline OPEX comprises power, fixed O&M from transport pipeline as well as a pipeline from port to storage site. Fixed O&M calculations are based 1% of CAPEX pertaining to each business case and the technical lifetime value.
Shuttle tanker/ vessel	CAPEX	Shuttle tanker/vessels CAPEX comprises acquisition price and export intermediate storage costs. For case 1, the acquisition price is based on a vessel of 20,000 t capacity in which 3 vessels are required. For the other cases, shuttle tankers of 20,000 t capacity are assumed. For business case 2B 3 shuttle tankers are needed. For 2A and 2C 4 shuttle tankers are required, while business case 3 requires 10 shuttle tankers. The additional capital expenditures attributed to the injection systems and intermediate storage onboard the vessels are covered in the storage CAPEX.
	OPEX	Shuttle tanker/vessels OPEX comprise fixed operations, maintenance, and fuel costs. The fixed O&M costs are based on 5% of shuttle tanker/vessel CAPEX pertaining to each business case and EUR 75/tCO2 export intermediate storage capacity. Fuel costs are based on the number of loading/unloading cycles, days per cycle, fuel consumption per day, cost of fuel and technical lifetime values. The additional operational expenditures attributed to the injection systems and intermediate storage onboard vessels are covered in storage OPEX.
Operations time period	Years of operation	It is assumed that the CO2 transport and storage projects have an operational lifetime of 30 years[233].
Operation start year	Year	2030 is the assumed start year of operation. CAPEX occurs in year 0, i.e. 2030, and in year 1, i.e. 2031, OPEX and revenues are applied.

[232] For case 1 storage instalment CAPEX comprise: Intermediate storage, Injection plant, Injection wells, Wellhead platform as well as Mooring and loading system. For case 2A this includes: Intermediate storage, Injection plant and Injection wells. For case 2B and 2C: Intermediate storage, Injection plant, Injection wells and Wellhead platform. For case 3: Intermediate storage, Injection plant, Injection wells as well as wellhead platform for nearshore and offshore storages.

[233] Ramboll expert

WACC	Financial costs	The WACC applied in all business cases are based on the European Commission's guide to cost-benefit analysis indicative benchmark value of investment projects, which is 4%.[234]

CO2 transport costs from shuttle tankers, vessels and pipelines are included in business cases 1, 2 and 3, although this could potentially be paid by the emitter or split between the emitter and the CO2 storage solution provider. If Denmark pays for the export countries' transport of CO2, the export countries will receive favourable conditions – especially in the less expensive onshore storage solution option. The cost of covering export countries' transport might be transferred to Danish emitters, which makes it more expensive for them, and Danish emitter might end up choosing storage solutions in competing countries. If CO2 is imported at a large scale it could be more feasible to cover the export countries' transport costs, since, with economies of scale, the price could come down.

Additionally, no liquefaction is assumed in any of the calculations of the cost of sea transportation. Liquefaction is a high cost, but if it is excluded in both our cost calculation and the references price (i.e. the applied revenue), then it matters not so much. Also, the cost for transportation by the sea does not include harbour fees. Liquefaction and harbour fees are typically included at the CO_2 capture plant. However, as both liquefaction and harbour fees are particular to sea transport, this could potentially enhance the business case for using pipeline transport.

6.4 KEY CONCLUSIONS ON THE PROFITABILITY OF THE CO2 STORAGE IN DENMARK

Four out of five cases result in positive NPV values within a 30-year lifetime and range from a payback period between 8-25 years. However, it is **pivotal to note that the assessed business cases take a point of departure in the assumption that there will be a business case for CO2 storage providers and the price will be a combination of, e.g., CO2 prices, CO2 taxes, grants etc**. However, the way in which the price is subsidised is not deemed necessary to assess the profitability and break-even of the business cases. Rather, it is important to forecast a price that is representative of a feasible market-based (i.e. competitive) scenario, and thus, we have developed a reference price for transport and storage, which is based on what it would cost for the export countries to export their CO2 to an offshore UK storage, which is deemed a representative, competitive and feasible alternative to Danish CO2 storage solutions. The reference price is based on an average of the various Danish offshore storage alternatives presented in the set-ups (Chapter 5.3), which is based on what it would cost for the export countries to export their CO2 to an offshore UK storage, which is deemed a representative, competitive and feasible alternative to Danish CO2 storage solutions. Further, utilising a reference price is seen as the most representative methodology, since forecasting the CO2 price and subsidy mechanisms includes high uncertainty and an array of the possible pathway (e.g., uncertainty around how income from CO2 prices, taxes and grants are allocated, since they are not solely allocated to CCS).

(large-scale international CCS solution), mainly due to the high revenue volumes per year (40 MtCO2/y), economies of scale from large-scale operations and from combining solutions, e.g., pipelines utilised for different types of storages. Furthermore, this case includes all types of storages, meaning that CAPEX is lower than if only offshore storage was applied. Although case 3 has a significantly higher total cost than the domestic cases, the investment payback (**payback period is 11 years**) is expected sooner than for case 1, 2B and 2C, again due to expected large CO2 volumes combined with economies of scale/ use of price-effective storage and transport solutions.

Although providing a clear advantage in the form of flexibility, Case 1 (small-scale, domestically focused case with sea transportation only) **results in a negative NPV (DKK ~ (2.0) billion)** and the **longest payback period (25 years)**. The main reason is that this case has a considerable higher OPEX than the rest of the domestically focused cases, and the highest cost per ton CO2 among all cases. However, it is important to note that the case is built on the assumption that only vessels will be used for the transportation of CO2 (which is the most expensive transportation solution) during the 30-year business case period. If the transportation is optimised during the ramp-up, by e.g. adding a pipeline of permanently moored FSU, the business case could potentially improve. At the same time, the revenue applied in the model is

[234] European Commission - Guide to cost-benefit analysis of investment projects

difficult to determine, and there is therefore associated uncertainty with regards to business case results – i.e. business case would improve at higher revenue.

Case 2C (medium-scale, domestically focused case, with offshore storage) – also an offshore option in case 2 - **posts an NPV of DKK ~2.1 billion** and a **payback period of 15 years**. While this is a positive NPV, it is more expensive than 2A, and 2C since offshore storage sites are more expensive than onshore and nearshore solutions.

Case 2A (medium-scale, domestically focused case, with onshore storage) **results in the second-highest NPV of DKK ~11.5 billion** and has the **shortest payback period (8 years)**. **Case 2B** (medium-scale, domestically focused case, with nearshore storage) has an **NPV of DKK ~5.5 billion and a payback period of 13 years**. This case has the highest CAPEX of all medium-size cases (i.e. 2A, 2B, 2C), however, OPEX is the second-lowest.

The results above are **based on a number of prerequisites**, including expected CO2 volumes, strong project management and identification of qualified, responsible parties, financial support (both nationally and in case 3 also internationally), that necessary permits are obtained without major delays, technological enhancement and ability to start the operations no later than 2030 (or at least in line with the volume uptake). Furthermore, some case-specific prerequisites apply, e.g. that the reservoirs (especially the less known onshore and nearshore storages) can be used for storage of CO2 and availability of the existing offshore pipeline infrastructure in time for the start of constructions works (and that it is possible to fully retrofit it to handle the large CO2 volumes) and that necessary international agreement, e.g. with German companies and state are secured up-front before the pipeline is constructed. For case 1 (small-scale and domestically focused case), one important prerequisite is that oil and gas companies possessing the concession rights are willing to switch from oil & gas activities to CO2 storage.

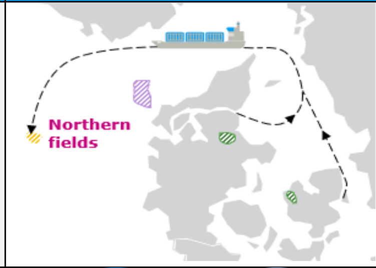
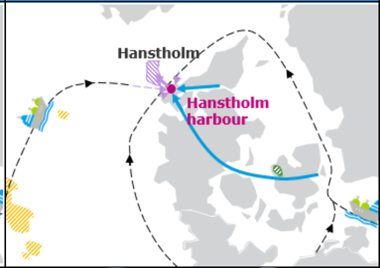
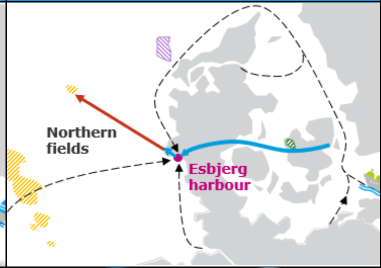
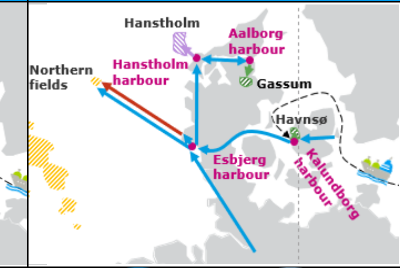
Furthermore, **pro's and con's have been compiled** for both domestically focused cases (case 1 and 2) and the case with international solution (case 3). It is important to highlight that the domestic-oriented solutions are less complex and more affordable options (especially case 2A, which offers a highly price competitive option, with the highest IRR and with the shortest pay-back period). However, when starting at a smaller scale, it can, in many cases, be more challenging to move towards large-scale and international market solutions than starting at a large scale from the beginning. On the other hand, the small-scale domestic case with vessel transportation (case 1) is the one providing the highest degree of flexibility, as it can be ramped up to the medium-size solution (or even large-scale, although choosing this way around can lead to lost opportunities), and modified into other solutions stepwise. Consequently, this case gives the possibility to explore the market before making the final decision on the strategic direction. However, this case has also the highest total cost per ton of CO2.

The internationally oriented solution (case 3) enables full utilisation of the market potential (and Denmark's strategic location, with close proximity to DE, SE, FI and PL) by offering a price competitive, convenient, and potentially binding solution. This solution can also play into the EU's plan to reach ambitious CO2 reduction targets and thus secure international financing and cost/risk-sharing. On the other hand, this solution is significantly more complex (however not unrealistic, as proven by the recent Baltic Pipe project), would imply a need for extensive state involvement and investments in widespread CCS infrastructure, and also require EU to cooperate in continuing to support and pass policies that will aid the CCS market. Furthermore, this solution is the most meaningful if planned at a large scale from the beginning - adding storages or infrastructure at a later time can impair this system's competitiveness and expected CO2 volumes.

The detailed cash flow results for each business case scenario are shown in the figures and tables in the following sub-sections, with a corresponding summary description of the results.

Table 48: Overview of the results from the assessment of the different business cases

Nearshore storage site · Onshore storage site · Offshore storage site · CO2 Pipelines · Repurposed pipelines · CO2 Shipping routes · Harbour

Category	**Case 1:** Small-scale domestically focused case with sea transportation	**Case 2A:** Medium-scale, domestically focused case, with onshore storage	**Case 2B:** Medium-scale, domestically focused case, with nearshore storage	**Case 2C:** Medium-scale, domestically focused case, with offshore storage	**Case 3:** Large-scale international CCS solution
Illustration of business case (see appendix for full size)					
NPV (DKK) and IRR	**NPV: ~ (2.0) bn** / **IRR: ~0.2%**	**NPV: ~11.5 bn** / **IRR: ~12%**	**NPV: ~5.5 bn** / **IRR: ~7%**	**NPV: ~2.1 bn** / **IRR: ~5%**	**NPV: ~26.6 bn** / **IRR: ~9%**
DKK/ton	172	82	109	132	101
Break-even year	2055	2038	2043	2045	2041
Pre-requisites	• The source countries will capture CO2 with the intention for storage and choose Denmark as the storage destination • It is possible to identify and appoint parties with operational and technical CCS expertise to represent the state in order to secure fair competition (i.e. to avoid monopolisation of the market) • Likewise, all of the cases will require financial aid in order to be operational, as none of the solutions can operate without subsidies and grants • All necessary permits can be obtained without major delays • Required technology developments are achieved. For both cases, it is, e.g. assumed that shuttle tankers up to at least 20,000 tonnes will become available in the future • Operations start in 2030. The payback period assumes that the CCS systems (both storages and transport infrastructure) can be built in time to start operations no later than 2030, or at least in line with the volume uptake				
	• Interest and willingness from the oil & gas companies with concession rights to switch from gas/oil to CO2 operations • Pumping technology on vessels are is proven to work efficiently and commercialised • Existing injection wells can be reused (other cases assume that new wells will be built) • This case assumes focus on domestic activities only and CO2 import from abroad is not comprised; In practice, once on vessels, CO2 can be transported	• Especially for case 2A, there is a prerequisite that all necessary permits can be obtained without major delays. Due to the onshore location of the site, there is a risk of public opposition and difficulty obtaining necessary permits. • Both for case 2A and 2B, it is a prerequisite that the reservoirs can be used for the storage of CO2. None of these sites has been drilled yet, and it will therefore be necessary to carry out seismic surveys as well as appraisal drilling		• The existent gas pipeline can be reused for CCS purposes	• The existent gas pipeline can be reused for CCS purposes • EU and/or individual collaboration countries will provide support for the development of a CCS system • Agreements with German companies and state are secured upfront before the pipeline is constructed

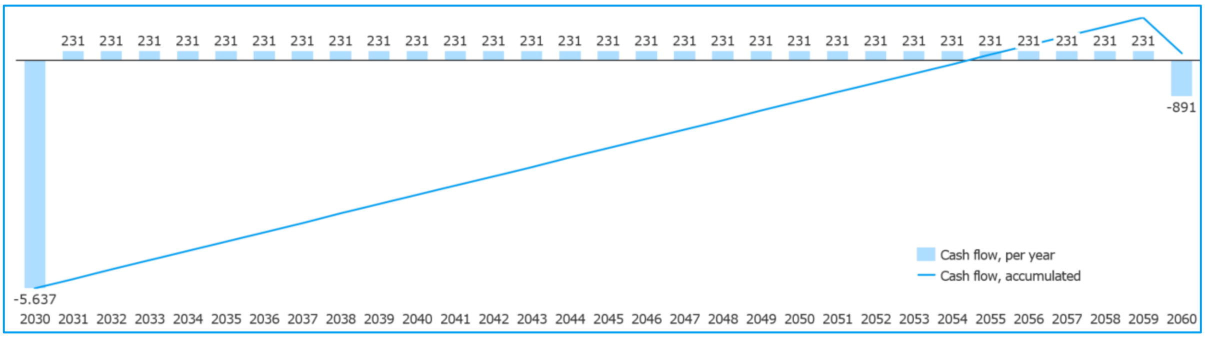
	from different locations (both domestically and internationally)		
Pro's	• This model gives a high degree of flexibility, as it can be re-evaluated and potentially changed/adjusted underway to match changing conditions and market needs. E.g. it is possible to switch to or add-on other solutions (e.g. a permanently moored FSU or pipeline that can optimise costs but also reduce flexibility) over time, when the market has been tested. It is also possible to add international markets any time, as the vessels can pick-up CO2 from various sources, also abroad • Relatively short construction time (~ 5 years) allows starting some operations already in 2026 (given that construction works start no later than in 2022) • Abandonment costs for existing oil & gas infrastructure can be postponed if it is reused for CO2 operations	• Less complex and affordable option: Especially case 2A offers a highly price competitive option, with the highest IRR and the shortest pay-back period • The domestically oriented solutions are more flexible with regards to a gradual build-up than the international case (as long as the focus remains on the domestic CO2 volumes). I.e. it is possible for this solution to start at a smaller scale and then add capacity as needed • CO2 transported via pipelines does not need to be liquefied. Although liquefaction is not included in this report (as it is considered to be part of carbon capture systems at source), it can be significant and result in additional costs for emitters	• Case with the highest NPV • Full utilisation of the market potential (and DK's strategic location, with close proximity to DE, SE, FI and PL) by offering a price competitive, convenient, and potentially binding solution • Ambitious EU targets for decarbonisation will most probably require CSS to close any potential gap in CO2 reductions, meaning that the project can receive financial support from EU and/or collaboration countries • A complex solution might imply more competition between players, and as such, the CCS might become more market-oriented • CO2 transported via pipelines does not need to be liquefied. Although liquefaction for sea transport is not included in this report (as it is considered to be part of carbon capture systems at source), it can be significant and result in higher costs for emitters
Con's	• Case 1 has the highest cost per ton among all cases, although it can be potentially improved over time if it is expanded to include more cost-efficient solutions • Likewise, in case 1, CO2 emitters/sources are not committed to Denmark (which would be the case with pipeline), implying a potentially higher risk of losing these customers to competition (especially given relatively high costs, which will presumably impact the price on CO2 transport and storage as well) • Vessels in case 1 are built for the purpose and can potentially become sunk cost if this solution is dropped or changed over time (i.e. are more difficult to retrofit to other purposes, than, e.g. shuttle tankers)	• Particularly onshore and nearshore solution can be difficult and potentially unprofitable to expand to the international scale later in time • Risk for public opposition against the onshore storage	• High project complexity meaning the risk to the timeline. However, the recent project experiences within the gas industry (Baltic Pipe) prove such complex solutions realistic • Need for extensive state involvement and investments in widespread CCS infrastructure. It will also require EU to cooperate in continuing to support and pass policies that will aid the CCS market • Only meaningful if the full infrastructure is planned from the beginning. Adding storages or infrastructure afterwards can impair the competitiveness of this system and also expected CO2 volumes

6.5 BUSINESS CASE DEEP-DIVES

6.5.1 Case 1 – Small-scale, domestically focused case, with offshore CO2 storage, but sea transportation only (no pipeline or ports assumed)

Case 1 posts a negative **NPV of DKK ~ (2.0) billion** and a **payback time of 25 years**. Thus, this case has the lowest NPV of all cases and the longest payback period due to the high OPEX, although this case does not have costs related to pipeline transport. The operational expenditure for vessels and storage (most significant contributors to this are the OPEX of wellhead platforms, standby vessels, and mooring and loading systems) are higher than the rest of case 2 options. The IRR is positive at **~ 0.2%**.

Figure 19: Cash flow case 1



Source: Ramboll analysis

Figure 20: Business case overview 1

YEAR	Unit	0	1	2	3	24	25	26	27	28	29	30
Year		**2030**	**2031**	**2032**	**2033**	**2054**	**2055**	**2056**	**2057**	**2058**	**2059**	**2060**
Revenue												
Reference price	DKK	169 kr.	169 kr.	169 kr.	169 kr.	169 kr.	169 kr.	169 kr.	169 kr.	169 kr.	169 kr.	169 kr.
CO2 volume		5	5	5	5	5	5	5	5	5	5	5
Total revenue	**mDKK**	**843 kr.**	**843 kr.**	**843 kr.**	**843 kr.**	**843 kr.**	**843 kr.**	**843 kr.**	**843 kr.**	**843 kr.**	**843 kr.**	**843 kr.**
OPEX												
Storage	mDKK		490 kr.	490 kr.	490 kr.	490 kr.	490 kr.	490 kr.	490 kr.	490 kr.	490 kr.	490 kr.
Vessels	mDKK		122 kr.	122 kr.	122 kr.	122 kr.	122 kr.	122 kr.	122 kr.	122 kr.	122 kr.	122 kr.
Pipeline	mDKK		0 kr.	0 kr.	0 kr.	0 kr.	0 kr.	0 kr.	0 kr.	0 kr.	0 kr.	0 kr.
Total operating expenditures	**mDKK**		**612 kr.**	**612 kr.**	**612 kr.**	**612 kr.**	**612 kr.**	**612 kr.**	**612 kr.**	**612 kr.**	**612 kr.**	**612 kr.**
EBITDA	**mDKK**		**231 kr.**	**231 kr.**	**231 kr.**	**231 kr.**	**231 kr.**	**231 kr.**	**231 kr.**	**231 kr.**	**231 kr.**	**231 kr.**
CAPEX												
Storage, Pre-FID cost (one-time cost)	mDKK	300 kr.										
Storage, Instalment costs	mDKK	2.980 kr.										
Storage, Abandonment cost (ABEX)	mDKK											522 kr.
Storage, Post-Closure Cost/Monitoring	mDKK											600 kr.
Vessels, acquisition cost	mDKK	1.419 kr.										
Export intermediate storage	mDKK	938 kr.										
Pipeline, Instalment costs	mDKK	0 kr.										
Total capital expenditures	**mDKK**	**5.637 kr.**	**0 kr.**	**0 kr.**	**0 kr.**	**0 kr.**	**0 kr.**	**0 kr.**	**0 kr.**	**0 kr.**	**0 kr.**	**1.122 kr.**
Depreciations												
	mDKK		188 kr.	188 kr.	188 kr.	188 kr.	188 kr.	188 kr.	188 kr.	188 kr.	188 kr.	1.309 kr.
EBIT	**mDKK**	**0 kr.**	**43 kr.**	**43 kr.**	**43 kr.**	**43 kr.**	**43 kr.**	**43 kr.**	**43 kr.**	**43 kr.**	**43 kr.**	**-1.078 kr.**
Cash flow	**mDKK**	**-5.637 kr.**	**231 kr.**	**231 kr.**	**231 kr.**	**231 kr.**	**231 kr.**	**231 kr.**	**231 kr.**	**231 kr.**	**231 kr.**	**-891 kr.**
Discounted cash flow	**mDKK**	**-5.637 kr.**	**222 kr.**	**213 kr.**	**205 kr.**	**90 kr.**	**87 kr.**	**83 kr.**	**80 kr.**	**77 kr.**	**74 kr.**	**-275 kr.**
Accumulated cash flow	**mDKK**	**-5.637 kr.**	**-5.406 kr.**	**-5.175 kr.**	**-4.944 kr.**	**-95 kr.**	**136 kr.**	**367 kr.**	**598 kr.**	**829 kr.**	**1.060 kr.**	**169 kr.**

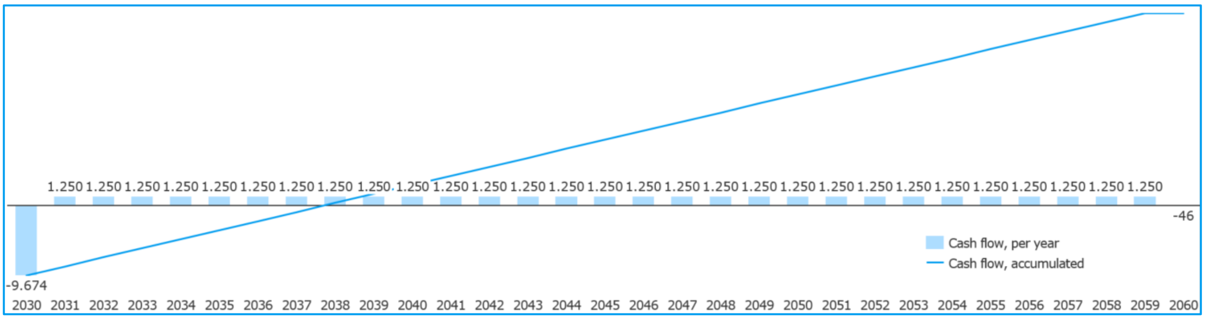
Present value (PV), mDKK	**DKK**	**3.647**
Net present value (NPV), mDKK	**DKK**	**(1.989)**
IRR		**0,2%**
WACC		**4%**

Source: Ramboll analysis

6.5.2 Case 2A – Medium-scale, domestically focused case, with onshore storage

Case 2A has an **NPV of DKK ~11.5 billion** and a **payback time of 8 years** in **2038**. The NPV is the highest of all business cases in the medium-scale option, whereas the payback period is the lowest of all business cases and is mainly due to OPEX and CAPEX for the onshore option being the lowest and the reference price applied is the same for all cases (except the price for case 3, which is slightly lower). The IRR also reflects these results and posts **~12%.**

Figure 21: Cash flow 2A



Source: Ramboll analysis

Figure 22: Business case overview 2A

YEAR	Unit	0	1	2	3	4	5	6	7	8	28	29	30
Year		**2030**	**2031**	**2032**	**2033**	**2034**	**2035**	**2036**	**2037**	**2038**	**2058**	**2059**	**2060**
Revenue													
Reference price	DKK	166 kr.	166 kr.	166 kr.	166 kr.	166 kr.	166 kr.	166 kr.	166 kr.	166 kr.	166 kr.	166 kr.	166 kr.
CO2 volume		10	10	10	10	10	10	10	10	10	10	10	10
Total revenue	**mDKK**	**1.663 kr.**	**1.663 kr.**	**1.663 kr.**	**1.663 kr.**	**1.663 kr.**	**1.663 kr.**	**1.663 kr.**	**1.663 kr.**	**1.663 kr.**	**1.663 kr.**	**1.663 kr.**	**1.663 kr.**
OPEX													
Storage	mDKK		188 kr.	188 kr.	188 kr.	188 kr.	188 kr.	188 kr.	188 kr.	188 kr.	188 kr.	188 kr.	188 kr.
Shuttle tanker/vessels	mDKK		209 kr.	209 kr.	209 kr.	209 kr.	209 kr.	209 kr.	209 kr.	209 kr.	209 kr.	209 kr.	209 kr.
Pipeline	mDKK		16 kr.	16 kr.	16 kr.	16 kr.	16 kr.	16 kr.	16 kr.	16 kr.	16 kr.	16 kr.	16 kr.
Total operating expenditures	**mDKK**		**413 kr.**	**413 kr.**	**413 kr.**	**413 kr.**	**413 kr.**	**413 kr.**	**413 kr.**	**413 kr.**	**413 kr.**	**413 kr.**	**413 kr.**
EBITDA	**mDKK**		**1.250 kr.**	**1.250 kr.**	**1.250 kr.**	**1.250 kr.**	**1.250 kr.**	**1.250 kr.**	**1.250 kr.**	**1.250 kr.**	**1.250 kr.**	**1.250 kr.**	**1.250 kr.**
CAPEX													
Storage, Pre-FID cost (one-time cost)	mDKK	308 kr.											
Storage, Instalment costs	mDKK	4.170 kr.											
Storage, Abandonment cost (ABEX)	mDKK												730 kr.
Storage, Post-Closure Cost/Monitoring	mDKK												566 kr.
Shuttle tankers, acquisition cost	mDKK	1.892 kr.											
Export intermediate storage	mDKK	2.625 kr.											
Pipeline, Instalment costs	mDKK	679 kr.											
Total capital expenditures	**mDKK**	**9.674 kr.**	**0 kr.**	**0 kr.**	**0 kr.**	**0 kr.**	**0 kr.**	**0 kr.**	**0 kr.**	**0 kr.**	**0 kr.**	**0 kr.**	**1.295 kr.**
Depreciations													
	mDKK		322 kr.	322 kr.	322 kr.	322 kr.	322 kr.	322 kr.	322 kr.	322 kr.	322 kr.	322 kr.	1.618 kr.
EBIT	**mDKK**	**0 kr.**	**927 kr.**	**927 kr.**	**927 kr.**	**927 kr.**	**927 kr.**	**927 kr.**	**927 kr.**	**927 kr.**	**927 kr.**	**927 kr.**	**-368 kr.**
Cash flow	**mDKK**	**-9.674 kr.**	**1.250 kr.**	**1.250 kr.**	**1.250 kr.**	**1.250 kr.**	**1.250 kr.**	**1.250 kr.**	**1.250 kr.**	**1.250 kr.**	**1.250 kr.**	**1.250 kr.**	**-46 kr.**
Discounted cash flow	**mDKK**	**-9.674 kr.**	**1.202 kr.**	**1.156 kr.**	**1.111 kr.**	**1.068 kr.**	**1.027 kr.**	**988 kr.**	**950 kr.**	**913 kr.**	**417 kr.**	**401 kr.**	**-14 kr.**
Accumulated cash flow	**mDKK**	**-9.674 kr.**	**-8.424 kr.**	**-7.174 kr.**	**-5.924 kr.**	**-4.674 kr.**	**-3.424 kr.**	**-2.174 kr.**	**-925 kr.**	**325 kr.**	**25.323 kr.**	**26.572 kr.**	**26.527 kr.**

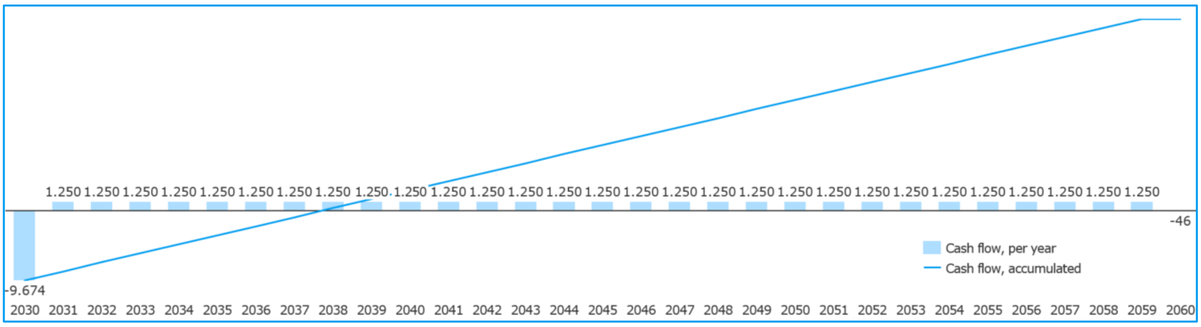
Present value (PV), mDKK	**DKK 21.213**
Net present value (NPV), mDKK	**DKK 11.540**
IRR	**12,49%**
WACC	**4,0%**

Source: Ramboll analysis

6.5.3 Case 2B – Medium-scale, domestically focused case, with nearshore storage

Case 2B has an **NPV of DKK ~5.5 billion** and a **payback time of 13 years** in **2043**. Thus, this case has a lower NPV and longer payback period than case 2A since the nearshore solution is more expensive than an onshore solution. This case has the second-highest total CAPEX of all options in case 2, however, OPEX is the second-lowest of all cases. The IRR is at **~7%.**

Figure 23: Cash flow 2B



Source: Ramboll analysis

Figure 24: Business case overview

YEAR	Unit	0	1	2	3	4	5	6	7	8	9	10	11	12	13	30
Year		**2030**	**2031**	**2032**	**2033**	**2034**	**2035**	**2036**	**2037**	**2038**	**2039**	**2040**	**2041**	**2042**	**2043**	**2060**
Revenue																
Reference price	DKK	166 kr.	166 kr.	166 kr.	166 kr.	166 kr.	166 kr.	166 kr.	166 kr.	166 kr.	166 kr.	166 kr.	166 kr.	166 kr.	166 kr.	166 kr.
CO2 volume		10	10	10	10	10	10	10	10	10	10	10	10	10	10	10
Total revenue	**mDKK**	**1.663 kr.**	**1.663 kr.**	**1.663 kr.**	**1.663 kr.**	**1.663 kr.**	**1.663 kr.**	**1.663 kr.**	**1.663 kr.**	**1.663 kr.**	**1.663 kr.**	**1.663 kr.**	**1.663 kr.**	**1.663 kr.**	**1.663 kr.**	**1.663 kr.**
OPEX																
Storage	mDKK		276 kr.	276 kr.	276 kr.	276 kr.	276 kr.	276 kr.	276 kr.	276 kr.	276 kr.	276 kr.	276 kr.	276 kr.	276 kr.	276 kr.
Shuttle tanker/vessels	mDKK		164 kr.	164 kr.	164 kr.	164 kr.	164 kr.	164 kr.	164 kr.	164 kr.	164 kr.	164 kr.	164 kr.	164 kr.	164 kr.	164 kr.
Pipeline	mDKK		48 kr.	48 kr.	48 kr.	48 kr.	48 kr.	48 kr.	48 kr.	48 kr.	48 kr.	48 kr.	48 kr.	48 kr.	48 kr.	48 kr.
Total operating expenditures	**mDKK**	**0 kr.**	**488 kr.**	**488 kr.**	**488 kr.**	**488 kr.**	**488 kr.**	**488 kr.**	**488 kr.**	**488 kr.**	**488 kr.**	**488 kr.**	**488 kr.**	**488 kr.**	**488 kr.**	**488 kr.**
EBITDA	**mDKK**	**1.663 kr.**	**1.175 kr.**	**1.175 kr.**	**1.175 kr.**	**1.175 kr.**	**1.175 kr.**	**1.175 kr.**	**1.175 kr.**	**1.175 kr.**	**1.175 kr.**	**1.175 kr.**	**1.175 kr.**	**1.175 kr.**	**1.175 kr.**	**1.175 kr.**
CAPEX																
Storage, Pre-FID cost (one-time cost)	mDKK	658 kr.														
Storage, Instalment costs	mDKK	7.086 kr.														
Storage, Abandonment cost (ABEX)	mDKK															1.240 kr.
Storage, Post-Closure Cost/Monitoring	mDKK															849 kr.
Shuttle tankers, acquisition cost	mDKK	1.419 kr.														
Export intermediate storage	mDKK	2.063 kr.														
Pipeline, Instalment costs	mDKK	2.950 kr.														
Total capital expenditures	**mDKK**	**14.175 kr.**	**0 kr.**	**0 kr.**	**0 kr.**	**0 kr.**	**0 kr.**	**0 kr.**	**0 kr.**	**0 kr.**	**0 kr.**	**0 kr.**	**0 kr.**	**0 kr.**	**0 kr.**	**2.089 kr.**
Depreciations																
	mDKK		473 kr.	473 kr.	473 kr.	473 kr.	473 kr.	473 kr.	473 kr.	473 kr.	473 kr.	473 kr.	473 kr.	473 kr.	473 kr.	2.561 kr.
EBIT	**mDKK**	**1.663 kr.**	**703 kr.**	**703 kr.**	**703 kr.**	**703 kr.**	**703 kr.**	**703 kr.**	**703 kr.**	**703 kr.**	**703 kr.**	**703 kr.**	**703 kr.**	**703 kr.**	**703 kr.**	**-1.386 kr.**
Cash flow	**mDKK**	**-14.175 kr.**	**1.175 kr.**	**1.175 kr.**	**1.175 kr.**	**1.175 kr.**	**1.175 kr.**	**1.175 kr.**	**1.175 kr.**	**1.175 kr.**	**1.175 kr.**	**1.175 kr.**	**1.175 kr.**	**1.175 kr.**	**1.175 kr.**	**-913 kr.**
Discounted cash flow	**mDKK**	**-14.175 kr.**	**1.130 kr.**	**1.087 kr.**	**1.045 kr.**	**1.005 kr.**	**966 kr.**	**929 kr.**	**893 kr.**	**859 kr.**	**826 kr.**	**794 kr.**	**763 kr.**	**734 kr.**	**706 kr.**	**-282 kr.**
Accumulated cash flow	**mDKK**	**-14.175 kr.**	**-13.000 kr.**	**-11.825 kr.**	**-10.650 kr.**	**-9.475 kr.**	**-8.299 kr.**	**-7.124 kr.**	**-5.949 kr.**	**-4.774 kr.**	**-3.599 kr.**	**-2.424 kr.**	**-1.248 kr.**	**-73 kr.**	**1.102 kr.**	**18.992 kr.**

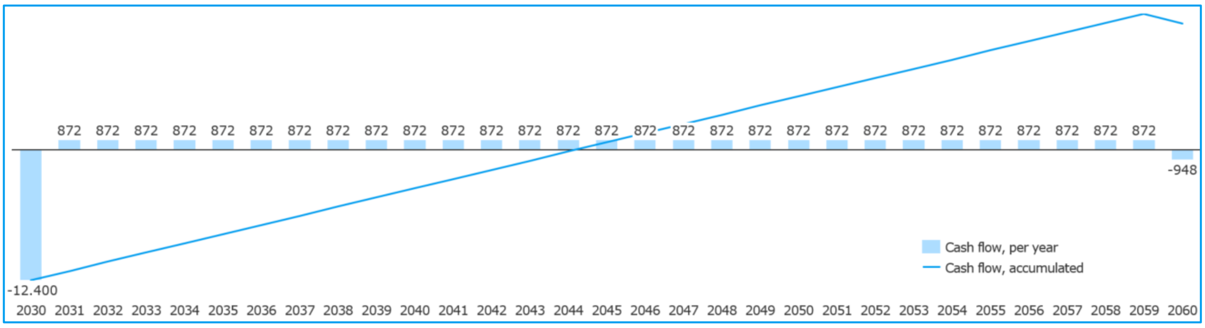
Present value (PV), mDKK	**DKK 19.678**
Net present value (NPV), mDKK	**DKK 5.502**
IRR	**7,1%**
WACC	**4,0%**

Source: Ramboll analysis

6.5.4 Case 2C – Medium-scale, domestically focused case, with offshore storage

Case 2C has an **NPV of DKK ~2.1 billion** and a **payback time of 15 years** in **2045**. Thus, this case has a lower NPV and longer payback period than case 2A and case 2B. This case has the second-highest total CAPEX of all options in case 2, however, OPEX is the second-lowest of all cases. The IRR is at **~6%**.

Figure 25: Cash flow 2C



Source: Ramboll analysis

Figure 26: Business case overview 2C

YEAR	Unit	0	1	2	3	10	11	12	13	14	15	30
Year		**2030**	**2031**	**2032**	**2033**	**2040**	**2041**	**2042**	**2043**	**2044**	**2045**	**2060**
Revenue												
Reference price	DKK	166 kr.	166 kr.	166 kr.	166 kr.	166 kr.	166 kr.	166 kr.	166 kr.	166 kr.	166 kr.	166 kr.
CO2 volume		10	10	10	10	10	10	10	10	10	10	10
Total revenue	**mDKK**	**1.663 kr.**	**1.663 kr.**	**1.663 kr.**	**1.663 kr.**	**1.663 kr.**	**1.663 kr.**	**1.663 kr.**	**1.663 kr.**	**1.663 kr.**	**1.663 kr.**	**1.663 kr.**
OPEX												
Storage	mDKK		547 kr.	547 kr.	547 kr.	547 kr.	547 kr.	547 kr.	547 kr.	547 kr.	547 kr.	547 kr.
Shuttle tanker/vessels	mDKK		210 kr.	210 kr.	210 kr.	210 kr.	210 kr.	210 kr.	210 kr.	210 kr.	210 kr.	210 kr.
Pipeline	mDKK		34 kr.	34 kr.	34 kr.	34 kr.	34 kr.	34 kr.	34 kr.	34 kr.	34 kr.	34 kr.
Total operating expenditures	**mDKK**		**791 kr.**	**791 kr.**	**791 kr.**	**791 kr.**	**791 kr.**	**791 kr.**	**791 kr.**	**791 kr.**	**791 kr.**	**791 kr.**
EBITDA	**mDKK**		**872 kr.**	**872 kr.**	**872 kr.**	**872 kr.**	**872 kr.**	**872 kr.**	**872 kr.**	**872 kr.**	**872 kr.**	**872 kr.**
CAPEX												
Storage, Pre-FID cost (one-time cost)	mDKK	170 kr.										
Storage, Instalment costs	mDKK	5.552 kr.										
Storage, Abandonment cost (ABEX)	mDKK											972 kr.
Storage, Post-Closure Cost/Monitoring	mDKK											849 kr.
Shuttle tankers, acquisition cost	mDKK	1.892 kr.										
Export intermediate storage	mDKK	2.625 kr.										
Pipeline, Instalment costs	mDKK	2.160 kr.										
Total capital expenditures	**mDKK**	**12.400 kr.**	**0 kr.**	**0 kr.**	**0 kr.**	**0 kr.**	**0 kr.**	**0 kr.**	**0 kr.**	**0 kr.**	**0 kr.**	**1.820 kr.**
Depreciations												
	mDKK		413 kr.	413 kr.	413 kr.	413 kr.	413 kr.	413 kr.	413 kr.	413 kr.	413 kr.	2.234 kr.
EBIT	**mDKK**	**0 kr.**	**458 kr.**	**458 kr.**	**458 kr.**	**458 kr.**	**458 kr.**	**458 kr.**	**458 kr.**	**458 kr.**	**458 kr.**	**-1.362 kr.**
Cash flow	**mDKK**	**-12.400 kr.**	**872 kr.**	**872 kr.**	**872 kr.**	**872 kr.**	**872 kr.**	**872 kr.**	**872 kr.**	**872 kr.**	**872 kr.**	**-948 kr.**
Discounted cash flow	**mDKK**	**-12.400 kr.**	**838 kr.**	**806 kr.**	**775 kr.**	**589 kr.**	**566 kr.**	**545 kr.**	**524 kr.**	**503 kr.**	**484 kr.**	**-292 kr.**
Accumulated cash flow	**mDKK**	**-12.400 kr.**	**-11.528 kr.**	**-10.656 kr.**	**-9.784 kr.**	**-3.681 kr.**	**-2.810 kr.**	**-1.938 kr.**	**-1.066 kr.**	**-194 kr.**	**678 kr.**	**11.935 kr.**

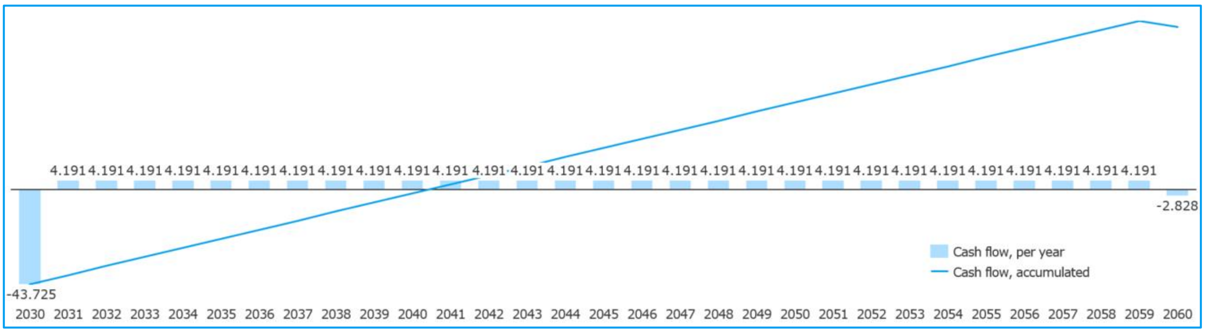
Present value (PV), mDKK	**DKK**	**14.514**
Net present value (NPV), mDKK	**DKK**	**2.115**
IRR		**5,4%**
WACC		**4%**

Source: Ramboll analysis

6.5.5 Case 3 – Large-scale international CCS solution

Case 2 has an **NPV of DKK ~26.6 billion** and a **payback time of 11 years** in **2041**. Thus, this case has the highest NPV of all cases, while the payback period is the second shortest (after case 2A). Naturally, this case it the most expensive in terms of both CAPEX and OPEX, however, the volumes are four times higher (40 MtCO2/y) than the options in case 2 and eight times higher than case 1 (although the reference price is just slightly lower than the other cases), which results in the case having the highest NPV. Further, this solution combines onshore, nearshore and offshore storages, as well as pipeline (including the assumption that existing gas pipelines can be utilised) and shuttle tanker transportation and this, results in a combination of solutions that provides economies of scale as well as synergies (e.g., the same pipeline can be used for more than one storage solution). The IRR is at **~9%**.

Figure 27: Cash flow 3



Source: Ramboll analysis

Figure 28: Business case overview 3

YEAR	Unit	0	1	2	3	4	5	6	7	8	9	10	11	30
Year		**2030**	**2031**	**2032**	**2033**	**2034**	**2035**	**2036**	**2037**	**2038**	**2039**	**2040**	**2041**	**2060**
Revenue														
Reference price	DKK	159 kr.	159 kr.	159 kr.	159 kr.	159 kr.	159 kr.	159 kr.	159 kr.	159 kr.	159 kr.	159 kr.	159 kr.	159 kr.
CO2 volume		40	40	40	40	40	40	40	40	40	40	40	40	40
Total revenue	**mDKK**	**6.367 kr.**	**6.367 kr.**	**6.367 kr.**	**6.367 kr.**	**6.367 kr.**	**6.367 kr.**	**6.367 kr.**	**6.367 kr.**	**6.367 kr.**	**6.367 kr.**	**6.367 kr.**	**6.367 kr.**	**6.367 kr.**
OPEX														
Storage	mDKK		1.518 kr.	1.518 kr.	1.518 kr.	1.518 kr.	1.518 kr.	1.518 kr.	1.518 kr.	1.518 kr.	1.518 kr.	1.518 kr.	1.518 kr.	1.518 kr.
Shuttle tanker/vessels	mDKK		437 kr.	437 kr.	437 kr.	437 kr.	437 kr.	437 kr.	437 kr.	437 kr.	437 kr.	437 kr.	437 kr.	437 kr.
Pipeline	mDKK		222 kr.	222 kr.	222 kr.	222 kr.	222 kr.	222 kr.	222 kr.	222 kr.	222 kr.	222 kr.	222 kr.	222 kr.
Total operating expenditures	**mDKK**		**2.176 kr.**	**2.176 kr.**	**2.176 kr.**	**2.176 kr.**	**2.176 kr.**	**2.176 kr.**	**2.176 kr.**	**2.176 kr.**	**2.176 kr.**	**2.176 kr.**	**2.176 kr.**	**2.176 kr.**
EBITDA	**mDKK**		**4.191 kr.**	**4.191 kr.**	**4.191 kr.**	**4.191 kr.**	**4.191 kr.**	**4.191 kr.**	**4.191 kr.**	**4.191 kr.**	**4.191 kr.**	**4.191 kr.**	**4.191 kr.**	**4.191 kr.**
CAPEX														
Storage, Pre-FID cost (one-time cost	mDKK	1.500 kr.												
Storage, Instalment costs	mDKK	22.882 kr.												
Storage, Abandonment cost (ABEX)	mDKK													4.004 kr.
Storage, Post-Closure Cost/Monitorin	mDKK													3.014 kr.
Shuttle tankers, acquisition cost	mDKK	4.730 kr.												
Export intermediate storage	mDKK	2.813 kr.												
Pipeline, Instalment costs	mDKK	11.799 kr.												
Total capital expenditures	**mDKK**	**43.725 kr.**	**0 kr.**	**0 kr.**	**0 kr.**	**0 kr.**	**0 kr.**	**0 kr.**	**0 kr.**	**0 kr.**	**0 kr.**	**0 kr.**	**0 kr.**	**7.019 kr.**
Depreciations														
	mDKK		1.457 kr.	1.457 kr.	1.457 kr.	1.457 kr.	1.457 kr.	1.457 kr.	1.457 kr.	1.457 kr.	1.457 kr.	1.457 kr.	1.457 kr.	8.476 kr.
EBIT	**mDKK**	**0 kr.**	**2.733 kr.**	**2.733 kr.**	**2.733 kr.**	**2.733 kr.**	**2.733 kr.**	**2.733 kr.**	**2.733 kr.**	**2.733 kr.**	**2.733 kr.**	**2.733 kr.**	**2.733 kr.**	**-4.285 kr.**
Cash flow	**mDKK**	**-43.725 kr.**	**4.191 kr.**	**4.191 kr.**	**4.191 kr.**	**4.191 kr.**	**4.191 kr.**	**4.191 kr.**	**4.191 kr.**	**4.191 kr.**	**4.191 kr.**	**4.191 kr.**	**4.191 kr.**	**-2.828 kr.**
Discounted cash flow	**mDKK**	**-43.725 kr.**	**4.030 kr.**	**3.875 kr.**	**3.726 kr.**	**3.582 kr.**	**3.444 kr.**	**3.312 kr.**	**3.185 kr.**	**3.062 kr.**	**2.944 kr.**	**2.831 kr.**	**2.722 kr.**	**-872 kr.**
Accumulated cash flow	**mDKK**	**-43.725 kr.**	**-39.534 kr.**	**-35.343 kr.**	**-31.152 kr.**	**-26.962 kr.**	**-22.771 kr.**	**-18.580 kr.**	**-14.390 kr.**	**-10.199 kr.**	**-6.008 kr.**	**-1.818 kr.**	**2.373 kr.**	**74.978 kr.**

Net present value (NPV), mDKK	**DKK 26.577**
IRR	**8,7%**
WACC	**4%**

Source: Ramboll analysis

6.6 BUSINESS CASE PREREQUISITES

All business cases presented in this chapter build on a number of prerequisites. Following prerequisites pertain to **all cases**:

- The source countries will capture CO2 with the intention for storage and choose Denmark as the storage destination
    - Particularly in Poland, there is a risk that the country might start storing CO2 on national territories in the future instead of exporting abroad
    - Additionally, it also requires all countries to choose CCS as the technology to remove these estimated capturable volumes instead of, e.g. CCU. Although the capturable volumes consider only the volumes intended for CCS, this is based on the current market, which can change over the years (due to technology development in other areas, political focus changes, etc.).
    - Furthermore, there is a general risk that the countries will fully or partly abandon the decarbonisation targets or incur serious delays in technology deployment due to possible unforeseen events
    - Another important risk related to potential CO2 volumes is that the biogenic emission will not be subject to carbon taxation, decreasing the incentives for carbon capture of these emissions
- It is possible to identify and appoint parties with operational and technical CCS expertise to represent the state in order to secure fair competition (i.e. to avoid monopolisation of the market). As mentioned in the chapter concerning institutional considerations, all cases will most likely require state involvement, a state-run body that upholds the strategic and administrative oversight of the project and parties (which to some degree represent the state/state-owned) with operational and technical expertise within CCS. Particularly case 2, which combines onshore, nearshore and offshore storage solutions, require increased governmental involvement
- Likewise, all of the cases will require financial aid in order to be operational, as none of the solutions can operate without subsidies and grants. In case of the large, internationally oriented solution (case 2), it is expected that EU and/or individual collaboration countries will provide support for the development of a CCS system, especially in a case, where a potential emission gap will be needed to be closed in order to reach the ambitious decarbonisation target set by EU for 2030 (reduction of the greenhouse gas emissions to at least 55% below 1990 levels by 2030). Furthermore, all cases outlined in this report comprise costs for the full infrastructure (i.e. both storage and transport of CO2 from source countries). Here it is also possible that transportation costs can be potentially shared with the emitters (e.g. cost for the pipeline from Germany or construction/acquisition of shuttle tankers). With reference to the bullet above, securing of the financing and potential cost-sharing requires proper and professional project management
- The offshore cases (2C and 3) underlie that an existent gas pipeline can be reused for CCS purposes. This means that the offshore pipeline infrastructure is available at the time constructions works to start and that retrofitting to handle the large CO2 volumes is possible
- Required technology developments are achieved. For both cases, it is, e.g. assumed that shuttle tankers up to at least 20,000 tonnes would become available in the future
- All necessary permits can be obtained without major delays. Especially the onshore storage can meet public opposition, resulting in the extended and potentially more uncertain permitting process than for the offshore storage
- Operations start no later than in 2030. The payback period assumes that the CCS systems (both storages and transport infrastructure) can be built in time to start operations no later than 2030, or at least in line with the volume uptake. In case of large delays, the risk is not only that the payback period will be longer, but also that volumes can be lost to competing storages. In practice, the full uptake of the CO2 volumes is not expected from year 1, and smaller delays or that only a share of operations can be carried during the first couple of years will not necessarily imply significant complications. Furthermore,

based on recent experience with the Baltic Pipe project, it is possible that all of the systems can be finalised even before 2030 (given that construction works can start already in 2022, the onshore and nearshore solutions could be completed in 2027 (expected timeline of ~6 years) and the offshore solution in 2026 (expected timeline of ~5 years; the shorter timeline is due to the possibility to reuse of some equipment and the geological structures being already known).

Other, **case-specific** prerequisites:

Case 1:

- Oil & gas companies with concession rights need to have interest and be willing to switch from gas/oil to CO_2 operations. A potential challenge could arise if oil and gas prices increase significantly, which can impact the willingness of these companies to stop exploiting before the governmentally set deadline. This could potentially require an incentive system
- By the time operations start, the onboard pumping technology has been fully developed and tested (and proven to work efficiently) and has been commercialised.

Case 2:

- Both for case 2A and 2B, it is a prerequisite that the reservoirs can be used for the storage of CO_2. None of these sites has been drilled yet, and it will therefore be necessary to carry out seismic surveys as well as appraisal drilling

Case 3:

- In order to be fully efficient, the solution outlined in case 3 requires that the full-scale infrastructure is constructed from the start (i.e. it is not meaningful to start small and expand later on). If a more gradual start is needed for this solution, then it is recommended to start with the offshore site, as it can be built fastest, and to avoid that price offered to customers increase significantly. Offshore solutions are assessed to be more expensive than onshore and nearshore solutions and will thus probably result in higher prices. High prices are expected to be more acceptable in the early stages of CCS, and the price is expected to become more competitive over time (which can be obtained by expanding with more price-competitive solutions).
- Collaboration and agreements with German companies and potentially state can be secured up front before the pipeline is constructed, i.e. the pipeline form source (e.g. Germany) will require some pre-work

6.7 PRO'S AND CON'S FOR THE ASSESSED BUSINESS CASES

The table below summarizes the key pro's and con's for case 1, 2 and 3, based on the insights gained in this chapter.

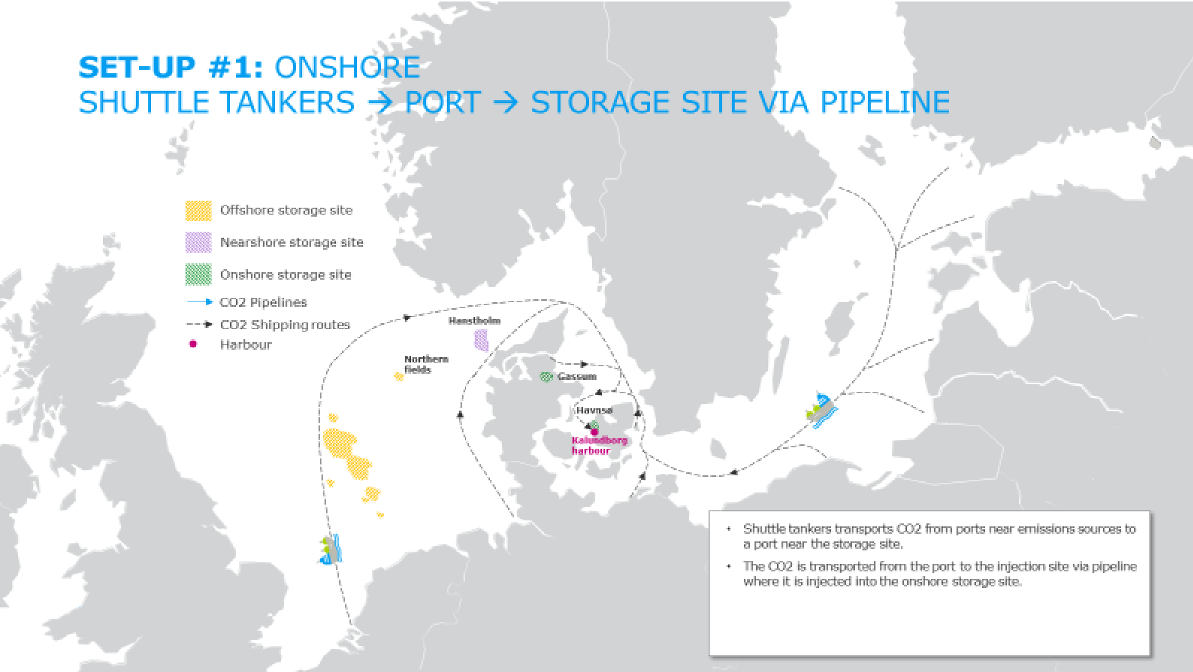
Table 49: Overview of pro's and con's for the assessed business cases

	Case 1 & 2 (A, B & C)	Case 3
Pro's	• Less complex and affordable option: Especially case 2A offers a highly price competitive option, and with the shortest pay-back period • All of the domestically oriented solutions are more flexible with regards to a gradual build-up than the international case (as long as the focus remains on the domestic CO2 volumes). I.e. it is possible for this solution to start at a smaller scale and then add capacity as needed in line with the market development • Especially case 1 gives a high degree of flexibility, as it can be re-evaluated and potentially changed/adjusted underway to match changing conditions and market needs. E.g. it is possible to switch to or add-on other solutions (e.g. a permanently moored FSU or pipeline that can optimise costs but also reduce flexibility) over time, when the market has been tested. It is also possible to add international markets any time, as the vessels can pick-up CO2 from various sources. • Relatively short construction time (~ 5 years) allows starting some operations already in 2026 (given that construction works start no later than in 2022) • Abandonment costs for existing oil & gas infrastructure can be postponed if it is reused for CO2 operations	• Case with the highest NPV • Denmark has a competitive advantage in terms of its location, being strategically located in close proximity to Germany, Sweden, Finland and Poland, to which it can offer both a convenient and price competitive solution, and thus secure CO2 volumes (especially from Germany via a pipeline) • Denmark is beside the NL, the only EU country which has shown willingness to develop storage capacity to store CO2 from other EU countries. The ambitious EU targets for decarbonisation will most probably require CSS to close any potential gap in CO2 reductions, meaning that the project can receive financial support from EU and/or collaboration countries • This case will entail that various player from both public and private bodies are involved and are responsible for different parts of the value chain. Since there are so many transport infrastructures laid out, it might involve more competition between players, and as such, CCS might become more market-oriented • CO2 transported via pipelines does not need to be liquefied. Although liquefaction is not included for sea transport in this report (as it is considered to be part of carbon capture systems at source), it can be significant and result in additional costs for emitters; Note that this advantage also applies to some degree for case 2
Con's	• Medium-scale solution (case 2, particularly 2A, onshore and 2B, nearshore) can be difficult and potentially unprofitable to expand to the international scale afterwards, as moving towards more expensive solutions can impair the competitiveness of the system (especially given that the market will move the opposite way, i.e. towards more price efficient solutions) • Risk for public opposition against onshore storage • In the case of 2C (offshore solution), the distance to the storage by ship is not significantly different from the offshore storage possibilities that UK or Norway is providing. Thus, there will be a potentially lower incentive for export countries to opt for storing their CO2 in Denmark. • Case 1 has the highest cost per ton among all cases, although it can be potentially improved over time if it is expanded to include more cost-efficient solutions • Likewise, in case 1, CO2 emitters/sources are not committed to Denmark (which would be the case with pipeline), implying a potentially higher risk of losing these customers to competition (especially given relatively high costs, which will presumably impact the price of CO2 transport and storage as well) • Vessels in case 1 are built for the purpose and can potentially become sunk cost if this solution is dropped or changed over time (i.e. are more difficult to retrofit to other purposes, than, e.g. shuttle tankers)	• High project complexity meaning risk to the timeline. However, the recent project experiences within gas industry (Baltic Pipe) provide a steppingstone for the development of such complex solutions. The Baltic pipe is expected to be completed in 2022, and thus only after a 5-year process, showcasing that timely completion of such projects is realistic • It will potentially require extensive state involvement and investments in widespread CCS infrastructure. It will also require the EU to cooperate in continuing to support and pass policies that will aid the CCS market • The international solution will be meaningful only in case when the full infrastructure is planned from the beginning. Adding storages or infrastructure afterwards can impair competitiveness of this system and the expected CO2 volumes

7. APPENDIX

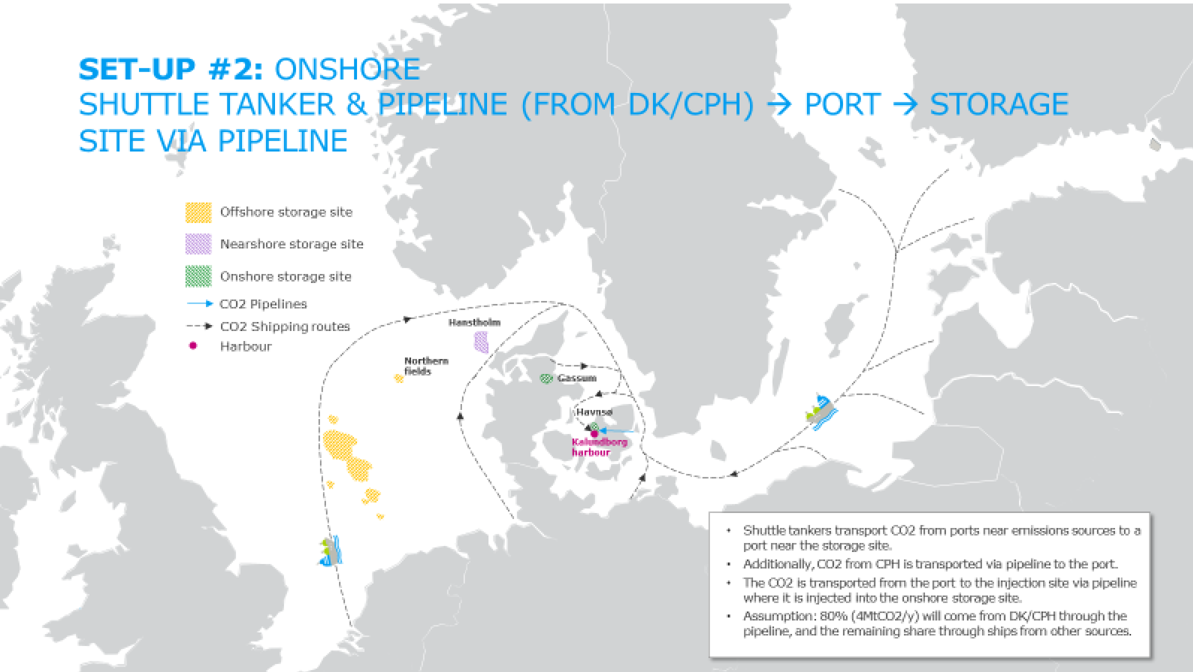
7.1 GRAPHICAL OVERVIEW OF BUSINESS MODEL SET-UPS

Figure 29: Set-up #1



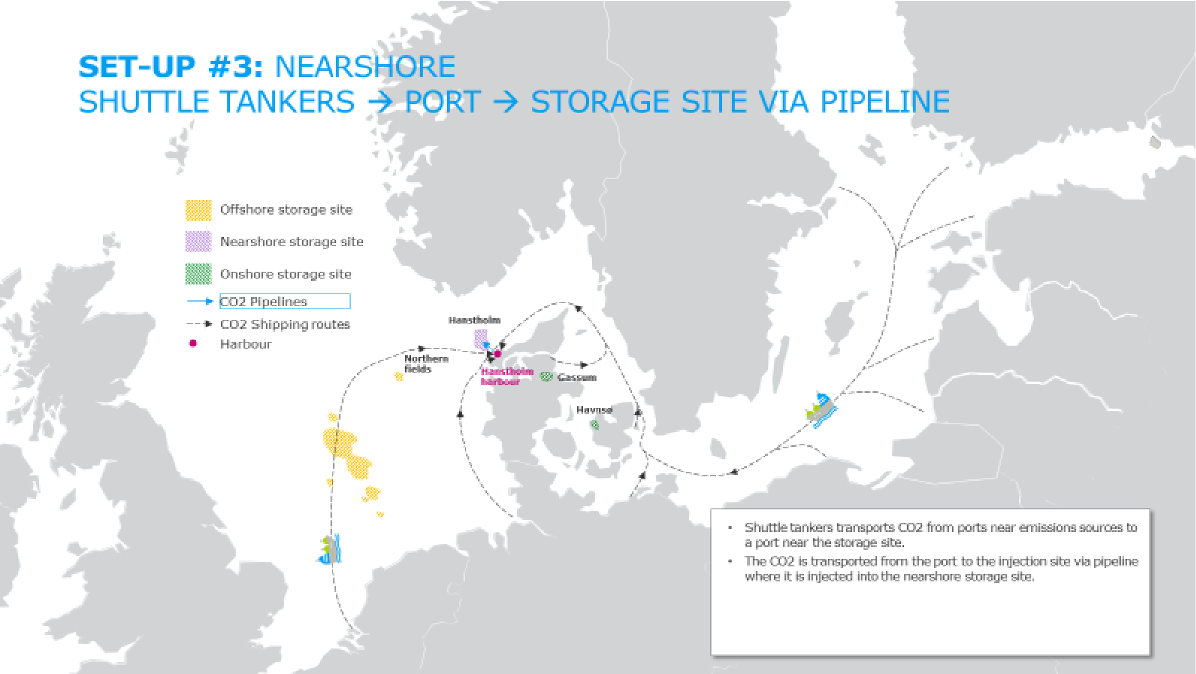
Source: Ramboll analysis; Ramboll & the Danish Energy Agency, "Catalogue of Geological CO2 Storage in Denmark"

Figure 30: Set-up #2



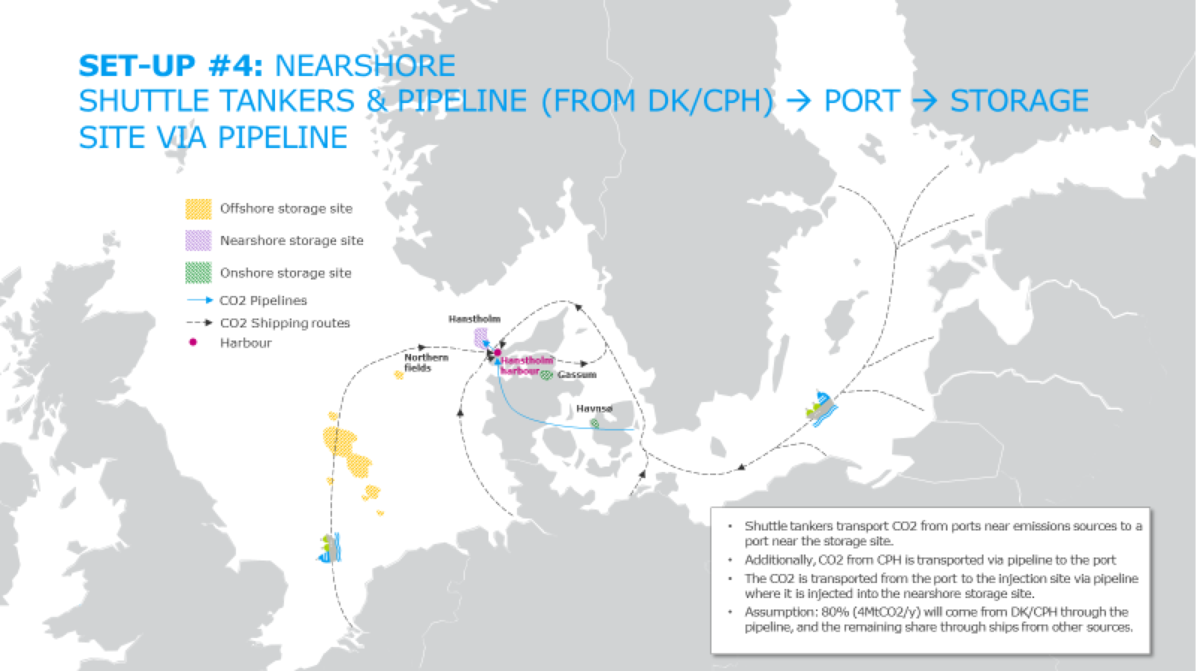
Source: Ramboll analysis; Ramboll & the Danish Energy Agency, "Catalogue of Geological CO2 Storage in Denmark"

Figure 31: Set-up #3



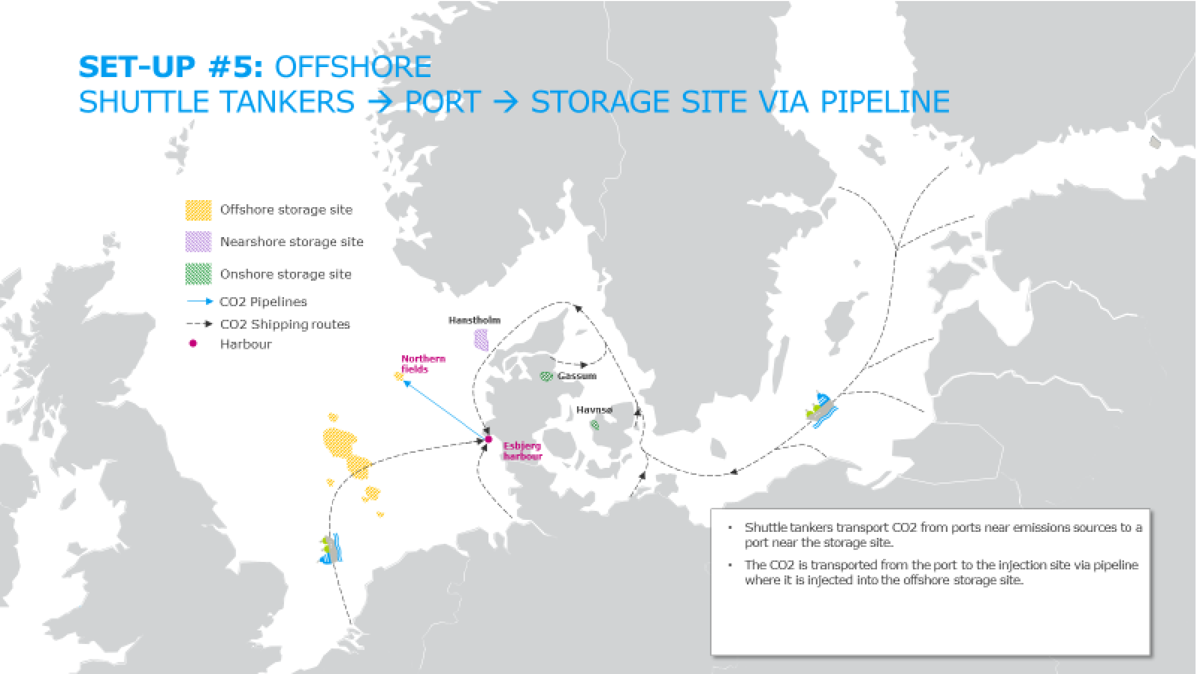
Source: Ramboll analysis; Ramboll & the Danish Energy Agency, "Catalogue of Geological CO2 Storage in Denmark"

Figure 32: Set-up #4



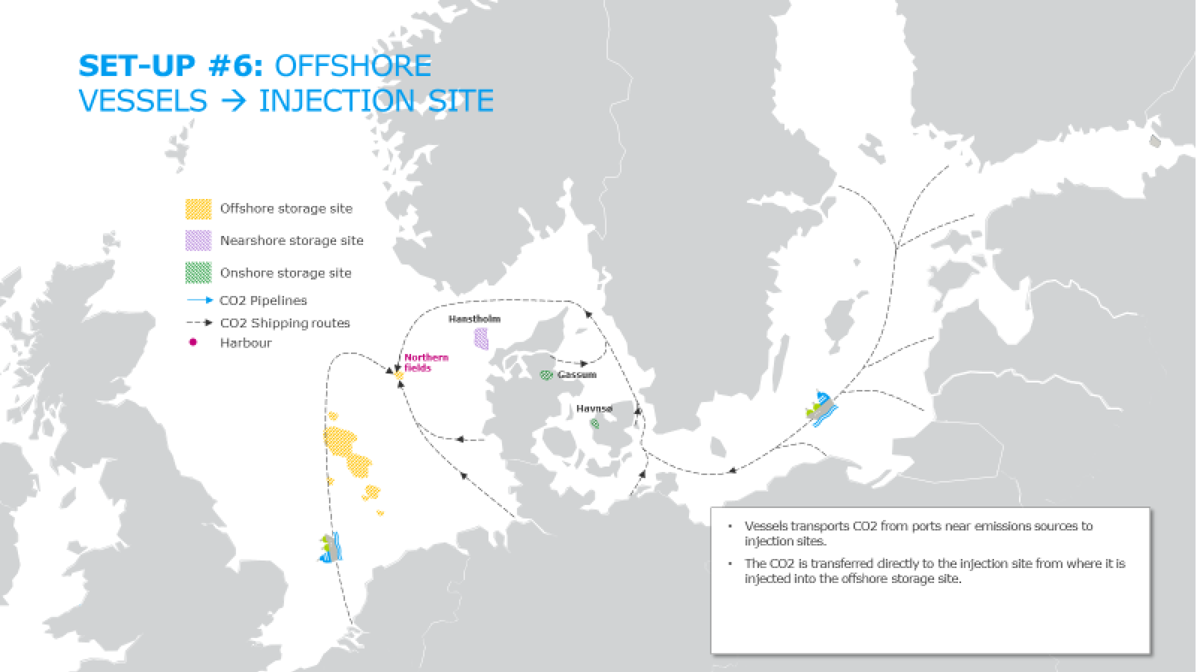
Source: Ramboll analysis; Ramboll & the Danish Energy Agency, "Catalogue of Geological CO2 Storage in Denmark"

Figure 33: Set-up #5



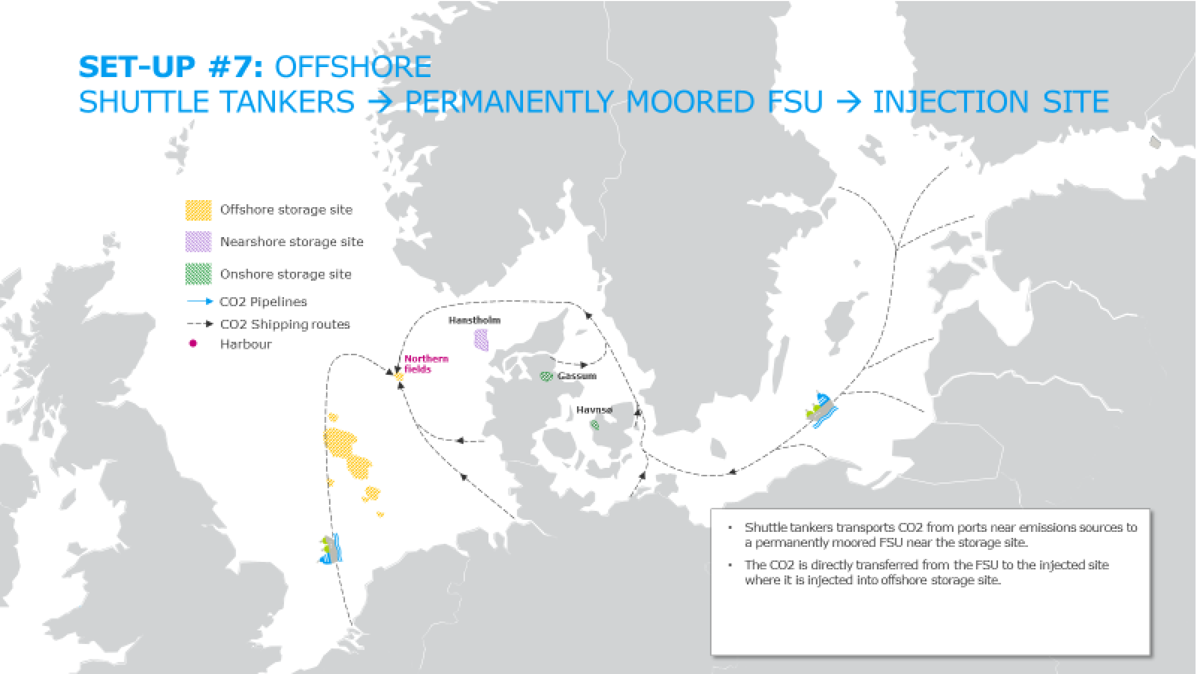
Source: Ramboll analysis; Ramboll & the Danish Energy Agency, "Catalogue of Geological CO2 Storage in Denmark"

Figure 34: Set-up #6



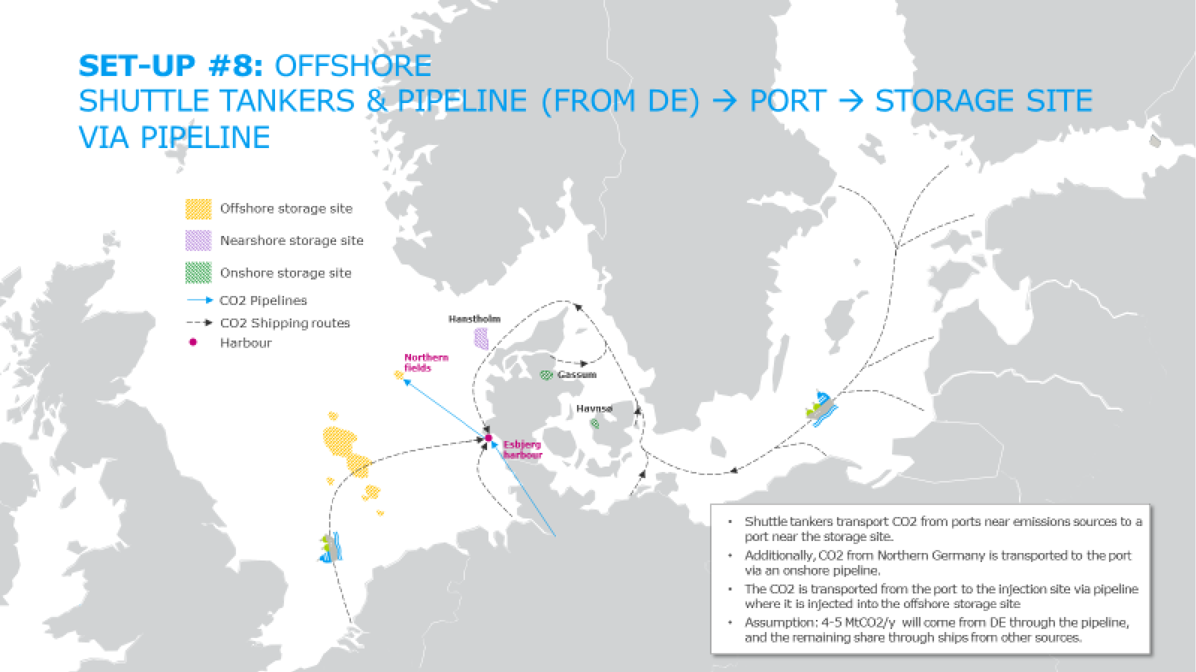
Source: Ramboll analysis; Ramboll & the Danish Energy Agency, "Catalogue of Geological CO2 Storage in Denmark"

Figure 35: Set-up #7



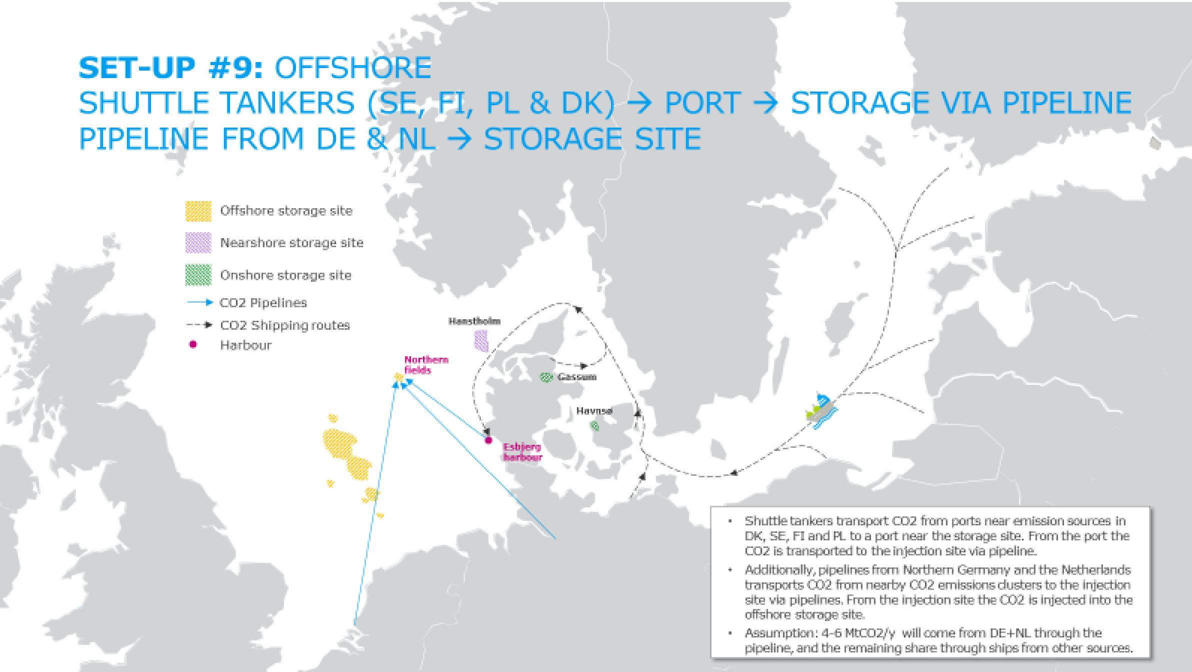
Source: Ramboll analysis; Ramboll & the Danish Energy Agency, "Catalogue of Geological CO2 Storage in Denmark"

Figure 36: Set-up #8



Source: Ramboll analysis; Ramboll & the Danish Energy Agency, "Catalogue of Geological CO2 Storage in Denmark"

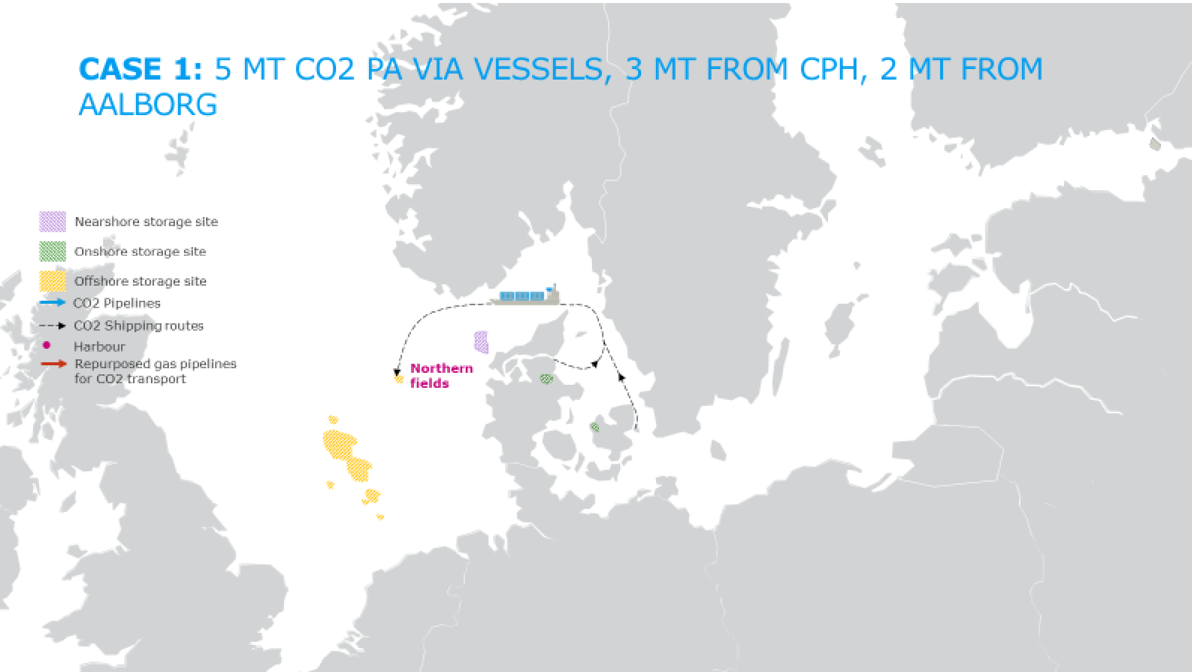
Figure 37: Set-up #9



Source: Ramboll analysis; Ramboll & the Danish Energy Agency

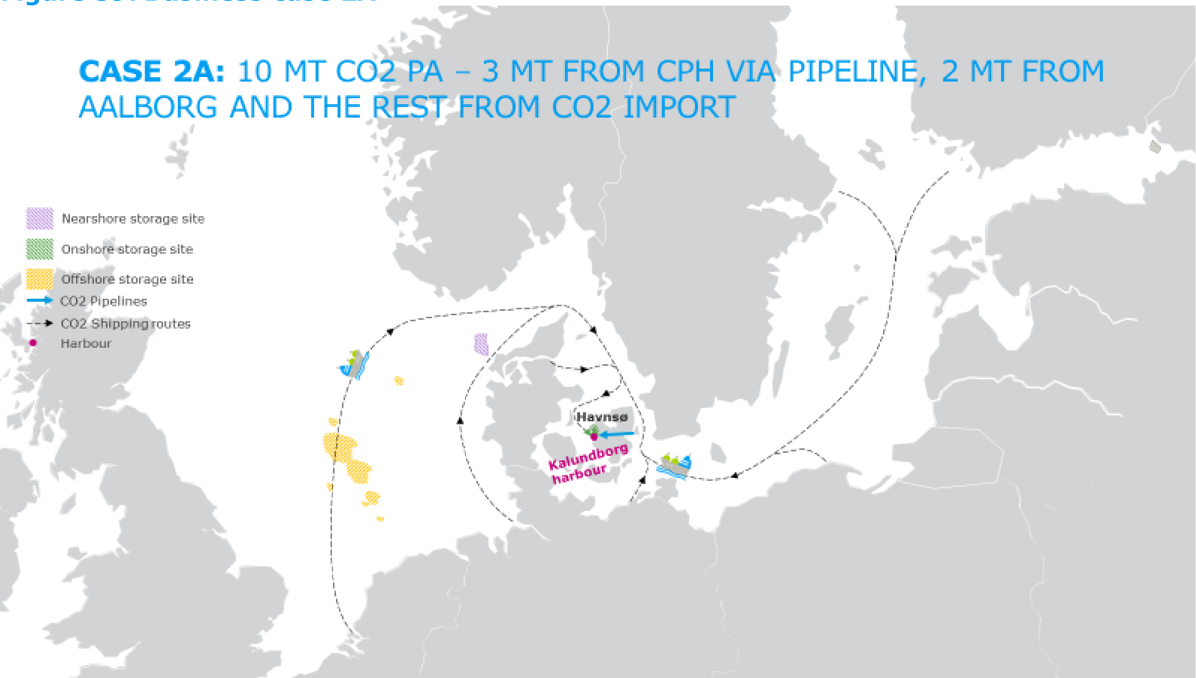
7.2 GRAPHICAL OVERVIEW OF BUSINESS CASES

Figure 38: Business case 1



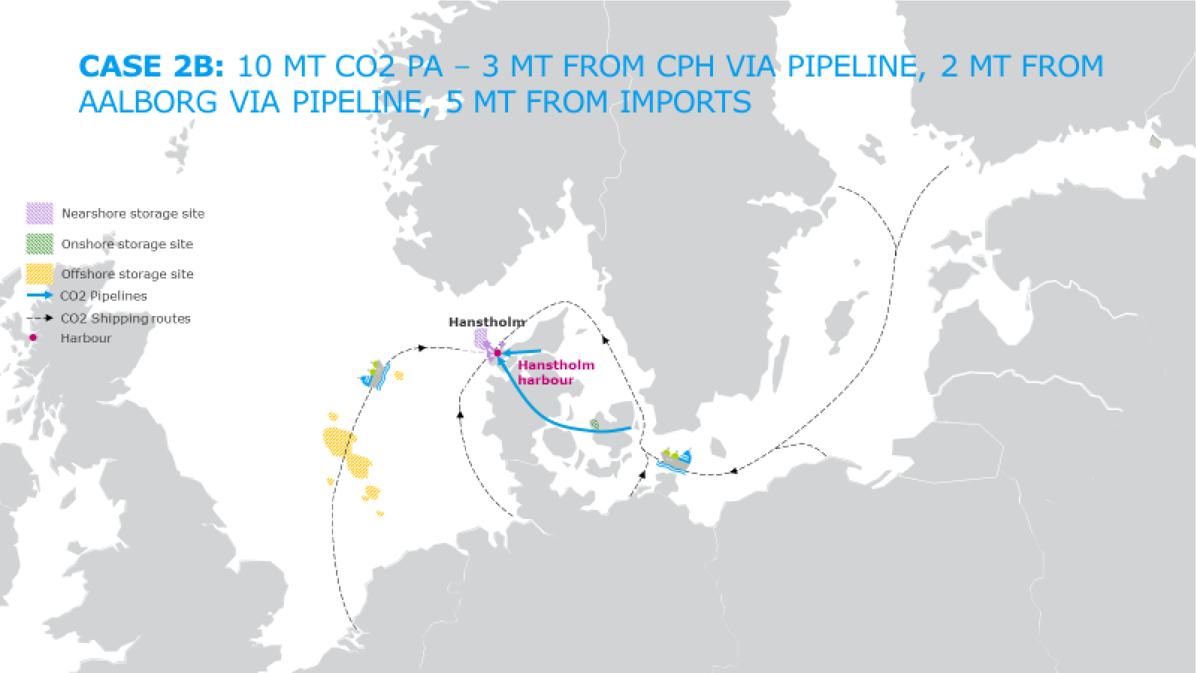
Source: Ramboll analysis; Ramboll & the Danish Energy Agency, "Catalogue of Geological CO2 Storage in Denmark"

Figure 39: Business case 2A



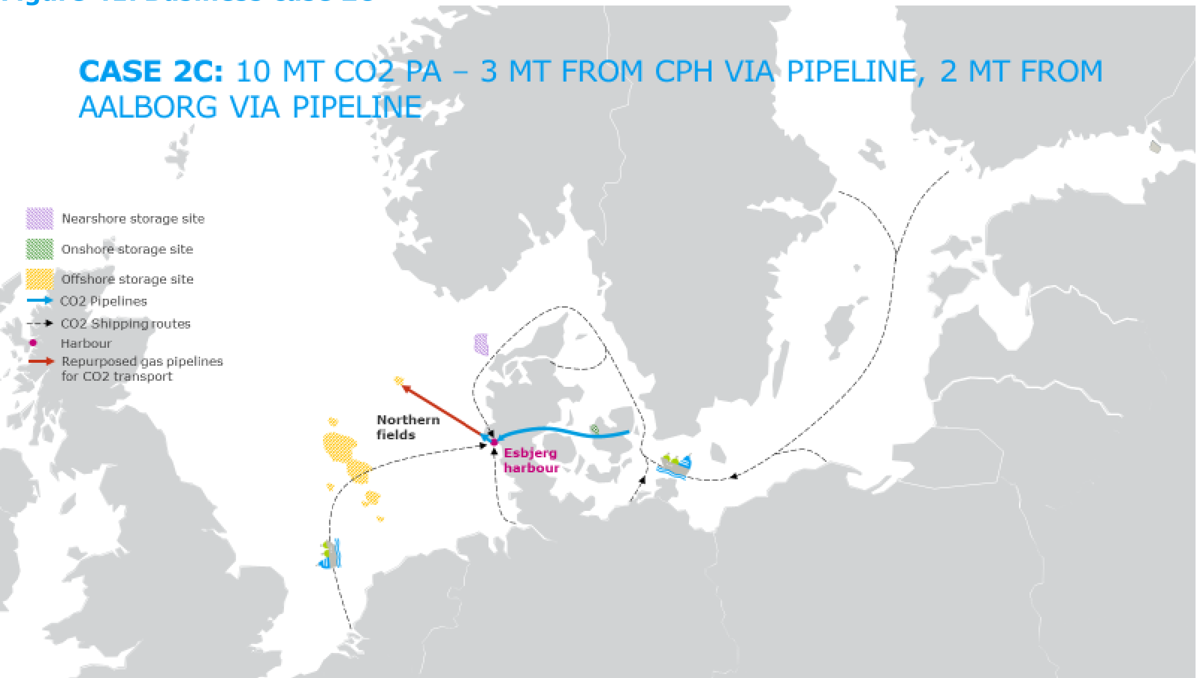
Source: Ramboll analysis; Ramboll & the Danish Energy Agency, "Catalogue of Geological CO2 Storage in Denmark"

Figure 40: Business case 2B



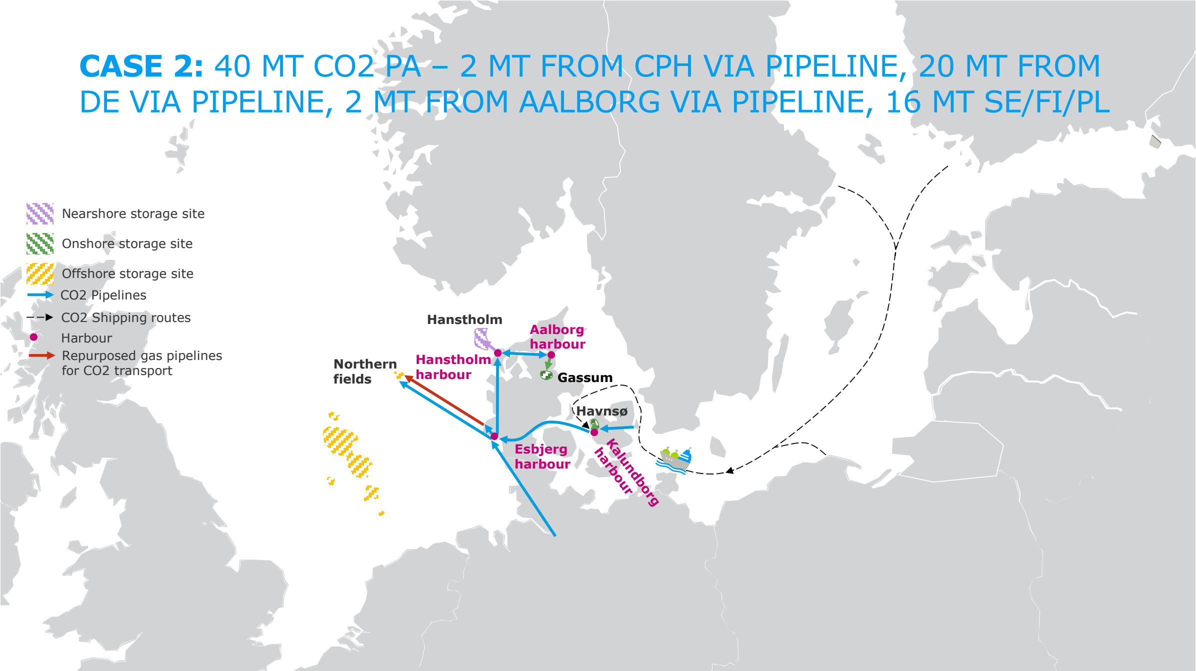
Source: Ramboll analysis; Ramboll & the Danish Energy Agency, "Catalogue of Geological CO2 Storage in Denmark"

Figure 41: Business case 2C



Source: Ramboll analysis; Ramboll & the Danish Energy Agency, "Catalogue of Geological CO2 Storage in Denmark"

Figure 42: Business case 3



Source: Ramboll analysis; Ramboll & the Danish Energy Agency, "Catalogue of Geological CO2 Storage in Denmark"

7.3 OVERVIEW OF COSTS AND ASSUMPTIONS PER BUSINESS MODEL SET-UP

This appendix section provides an overview of the cost for establishing and operating nine different CO2 transportation and storage set-ups based in Denmark.

Storage cost covers the cost of establishing, maintaining, and monitoring CO2 injection facilities and CO2 storage sites.

Transport cost covers the cost of transporting CO2 from ports near emission sources in five Northern European countries and domestically in Denmark to a Danish intermediate storage facility near a storage site. The costs are provided for the nine proposed setups identified in chapter 5.

Mapping of available options for transport and storage in Denmark, as well as cost estimates, is based on Catalogue of Geological Storage of CO2 in Denmark (to be published by Danish Energy Agency and Ramboll in 2021) and Catalogue on Technology Data for Energy Transport published by the Danish Energy Agency and Energinet (2017). Cost estimates from these sources have been supplemented by Ramboll's technical and commercial insights in connection with applying the costs to specific set-ups and scaling up.

The cost estimates follow the general assumptions outlined below:

- **The technical project lifetime** is assumed to be 30 years. While some equipment may have shorter lifetimes and some may have longer lifetimes, the average lifetime of equipment is expected to be 30 years. As a result, the accumulated OPEX of the project should supposedly cover 30 years of full operational expenditures. However, since ramping of injection rates to the assumed capacities is expected to take some years, the lifetime of the project at full operational capacity is expected to be effectively 27 years. As the operational expenditures are expected to ramp with the injection rate, the accumulated OPEX for the project will be reduced from covering 30 years to covering 27 years of full operational expenditures
- **Upgrading or retrofitting existing facilities** have not been included in the cost estimates of the set-ups, meaning all infrastructure associated with the project must be built from new
- **OPEX**
  - **Storage**: Covers storage facilities, injection facilities, wellhead platforms, wells, pipelines, mooring/loading systems, and FSUs which are based on offshore oil and gas industry norms, effectively percentages of CAPEX. This also includes monitoring, energy, standby vessels, base organisation, and staff
  - **Transport:** Covers fixed O&M for shuttle tankers, vessels, intermediate storage at export sites, onshore and offshore pipelines. It also includes fuel used during transportation
- **CAPEX**
  - **Storage:** Covers storage facilities, wellhead platforms, wells, pipelines, mooring/loading systems, and FSUs which are based on standards from the oil and gas industry and the size of the main components. This also covers any support systems for the facilities
  - **Transport:** Covers shuttle tankers, vessels, onshore and offshore pipeline, and any pumping stations associated with the pipelines
- **Pre-FID cost for storage** are incurred prior to final investment decision and are required to ensure the geological structures can store CO2 and to obtain the necessary approvals for establishing CO2 storage sites

- **Intermediate storage** is used at the port receiving the CO2 as a buffer for delays. A capacity of 50,000 t of intermediate storage was adequate for a 5 MtCO2/y scenario, which, assuming the logistics are well optimised, will also be adequate for the 10 MtCO2/y scenarios presented below. Capacity is considered to cost 2,500 EUR/t.
- **Ships (shuttle tankers and vessel)** for CO2 transport of the proposed size (20,000 t net capacity) have not yet been developed but is widely expected to be, and as a result, costs have been extrapolated using the cost of smaller ships as a basis
    - **Shuttle tankers** carry equipment for loading and unloading to and from intermediate storage facilities
    - **Vessels** carry injection and intermediate storage capabilities
- **A floating storage unit (FSU)** is a permanently moored vessel with injection and intermediate storage facilities where costs have been benchmarked against similar LNG FSUs. It only applies to offshore storage
- **Energy consumption** at onshore injection facilities is expected to be covered by electricity from the grid, where the cost of connection is included in the CAPEX of storage, pipeline, and injection facilities. Nearshore injection facilities are assumed to be connected by an AC electricity cable to the onshore grid, which will cover energy consumption. The cost of the AC cable is included in the CAPEX cost of the nearshore pipeline. Offshore operations (injection and intermediate storage) are assumed to connect to existing energy providing infrastructure in the North Sea. This means the cost of constructing the infrastructure that provides energy to the offshore operations is not included
- **Distances from exporting countries** are estimated based on the positions of ports near the largest emission clusters in a given country
- **Abatement expenditures ABEX** includes the port-to-storage pipelines, but not the transport pipelines, which are assumed can be repurposed after end-of-service, similarly to current oil and gas pipelines
- **Cost estimates do not consider** compensation to the local community for the loss of property value in the vicinity of the CO2 storage site or facilities. Furthermore, costs related to upgrading of port facilities (jetty, quayside, etc.), liquefaction of CO2 at export ports and any harbour fees related to docking have not been included

Table 50: Specific assumptions table

Overview of specific assumptions			
Name	**Unit**	**Value**	**Comments**
CO2 pipeline flow power	kW/km/(t CO2/h)	0.02	The amount of power it takes to pump a certain mass of CO2 a certain flow rate
Cost, heavy fuel oil (HFO)	EUR/ton	270	Assumed average price of HFO
Cost, intermediate storage capacity	EUR/t	2500	CAPEX cost of establishing intermediate storage capacity
Cost, shuttle tanker/vessel	MDKK	473	Cost of acquiring a CO2 shuttle tanker/vessel with 20,000 t net capacity
Energy consumption, shuttle tankers/vessels	MWh/day	256	The assumed energy consumption of a ship transporting 20,000 net ton of CO2 when at sea
Loading/unloading time per cycle, shuttle tanker	Days	1	The accumulated time it takes to load and unload a shuttle tanker per cycle
Loading/unloading time per cycle, vessel	Days	2	The accumulated time it takes to load and unload a vessel per cycle

Lower calorific value, heavy fuel oil (HFO)	MJ/kg	39.0	Amount of energy assumed to be extracted from HFO in a marine ICE engine
Pipeline, onshore, 3 MtCO2/y	MDKK/km	2.9	Assumed cost of onshore pipeline with 3 MtCO2/y capacity, based on oil and gas industry standards
Pipeline, onshore, 5 MtCO2/y	MDKK/km	3.5	Assumed cost of onshore pipeline with 5 MtCO2/y capacity, based on oil and gas industry standards
Pipeline, onshore, 10 MtCO2/y	MDKK/km	5.3	Assumed cost of onshore pipeline with 10 MtCO2/y capacity, based on oil and gas industry standards
Pipeline, onshore, 20 MtCO2/y	MDKK/km	7.0	Assumed cost of onshore pipeline with 20 MtCO2/y capacity, based on oil and gas industry standards
Pipeline, offshore, long 5 MtCO2/y	MDKK/km	7.0	Assumed cost of an offshore pipeline with 5 MtCO2/y capacity and no electricity cable, based on oil and gas industry standards
Pipeline, offshore, long 10 MtCO2/y	MDKK/km	11.0	Assumed cost of an offshore pipeline with 10 MtCO2/y capacity and no electricity cable, based on oil and gas industry standards
Pipeline, offshore, short 5 MtCO2/y	MDKK/km	7.0	Assumed cost of an offshore pipeline with 5 MtCO2/y capacity laid nearshore with an AC electricity cable, based on oil and gas industry standards
Pipeline, offshore, short 10 MtCO2/y	MDKK/km	11.0	Assumed cost of an offshore pipeline with 5 MtCO2/y capacity laid nearshore with an AC electricity cable, based on oil and gas industry standards
Pumping station, 3 MtCO2/y	MDKK	70	The pumping stations are placed every 200 km onshore transport pipelines or at each end of offshore transport pipelines
Pumping station, 5 MtCO2/y	MDKK	117	Pumping stations are placed every 200 km onshore transport pipelines or at each end of offshore transport pipelines
Pumping station, 10 MtCO2/y	MDKK	233	Pumping stations are placed every 200 km onshore transport pipelines or at each end of offshore transport pipelines
Pumping station, 20 MtCO2/y	MDKK	467	Pumping stations are placed every 200 km onshore transport pipelines or at each end of offshore transport pipelines
Utilisation rate, shuttle tankers	%	95	Expected rate of utilisation of the shuttle tankers, due to maintenance and routine inspections
Utilisation rate, vessel	%	90	Expected rate of utilisation of the vessels, due to maintenance and routine inspections

More details regarding specific assumptions and methodology for cost estimation are available in the Catalogue of Geological Storage of CO2 in Denmark published by the Danish Energy Agency and Ramboll in 2021 and the Catalogue on Technology Data for Energy Transport published by the Danish Energy Agency and Energinet (2017).

Estimated costs for each set-up are presented below. N**ote that the numbers do not include levelized cost of storage.**

OPTION #1: Onshore, shuttle tanker to Kalundborg harbour, then to Havnsø via pipeline

Table 51: Overview option #1

	Cost category	Unit	5 MtCO2/y	10 MtCO2/y	Comment
STORAGE	**Pre-FID**				
	2D seismic	MDKK	*90*	*127*	Based on the size of the area to be assessed
	Baseline studies	MDKK	*20*	*28*	Surveys all relevant pre-injection data
	Appraisal well	MDKK	*55*	*110*	The number of appraisal wells increases linearly with the size of the area to be appraised
	FEED studies	MDKK	*10*	*14*	Front end engineering design
	Approvals	MDKK	*20*	*28*	Regulatory approvals for establishing CO2 storage sites
	Total pre-FID costs	**MDKK**	**195**	**308**	
	CAPEX				
	Intermediate storage	MDKK	*180*	*180*	Assumed storage size of 50,000 t
	Injection plant	MDKK	*420*	*840*	Includes booster pumps, heat exchangers and boiler system
	Pipeline	MDKK	*140*	*212*	The pipeline between storage and injection site; cost is based on the length and industry-standard per km cost
	Injection wells	MDKK	*1,575*	*3,150*	The number of injection wells scales linearly to accommodate natural injection rate limitations of the storage site
	Wellhead platform	MDKK	*n/a*	*n/a*	The offshore structure that supports injection wells and associated support systems
	Mooring/loading system	MDKK	*n/a*	*n/a*	System for mooring and/or unloading CO2 offshore
	Purpose built CO2 carrier / FSU	MDKK	*n/a*	*n/a*	Permanently moored FSUs near offshore storage site have intermediate storage and injection capabilities
	Total CAPEX	**MDKK**	**2,315**	**4,382**	
	Acc. OPEX				
	Base organisation	MDKK	*175*	*247*	Covers day-to-day operations of the organisation
	Intermediate storage	MDKK	*223*	*223*	Facility size remains constant as additional buffer size does not provide value
	Injection plant	MDKK	*521*	*1,042*	The accumulated variable cost for operating the injection plant systems
	Pipeline	MDKK	*38*	*57*	Costs are evaluated as 1% of CAPEX per year for the full technical lifetime period
	Injection wells	MDKK	*427*	*854*	The accumulated variable cost of operating wells for injection of CO2 into subsurface reservoirs

		Monitoring	MDKK	*670*	*948*	Post-injection monitoring is only evaluated over a 20-year period
		Power	MDKK	*884*	*1,768*	Power scales linearly with the project size and is based on 0.5 DKK/KWh pricing
		Wellhead platform	MDKK	*n/a*	*n/a*	Accumulated variable cost for operating the wellhead platform
		Standby vessel	MDKK	*n/a*	*n/a*	Scales linearly with the number of vessels expected to be near the storage site
		Mooring/loading system	MDKK	*n/a*	*n/a*	Accumulated variable cost for operating the mooring/loading system offshore
		Purpose built CO2 carrier / FSU	MDKK	*n/a*	*n/a*	Accumulated variable cost for operating the FSU offshore
		Total acc. OPEX	**MDKK**	**2,938**	**5,139**	
		Closure costs				
		Abandonment cost	MDKK	*405*	*767*	Evaluated as 17,5% of total storage CAPEX
		Post-Closure cost	MDKK	*400*	*566*	Cost of monitoring the storage site post-closure
		Total closure costs	**MDKK**	**805**	**1,333**	
CO2 TRANSPORT	**Shuttle tanker/ Vessel**	**CAPEX**				
		Transport shuttle	MDKK	*1,419*	*2,365*	Import via shuttle tankers is assumed to be 100% of the import volume
		Vessel	MDKK	*n/a*	*n/a*	The additional cost of equipment for the vessels is included in the CAPEX and OPEX for storage
		Export intermediate storage	MDKK	*2,250*	*2,625*	Total export intermediate storage is 120,000 t and 140,000 t for each scenario, respectively, split between the exporting countries relative to their expected export volume
		Total CAPEX	**MDKK**	**3,669**	**4,990**	
		Acc. OPEX	MDKK			
		Transport shuttle fixed O&M	MDKK	*3,738*	*5,319*	5% of CAPEX + 75 EUR/ton export intermediate storage per year over the full technical project lifetime
		Vessels fixed O&M	MDKK	*n/a*	*n/a*	5% of CAPEX + 75 EUR/ton export intermediate storage per year over the full technical project lifetime
		Fuel	MDKK	*673*	*1,347*	Shuttle tankers during transport are assumed to consume 256 MWh per day, which drives fuel costs
		Total acc. OPEX	**MDKK**	**4,412**	**6,666**	

	Pipeline	**CAPEX**				
		Onshore pipeline	MDKK	*n/a*	*n/a*	Based on industry-standard price per km for pipelines of the assumed capacity
		Offshore pipeline	MDKK	*n/a*	*n/a*	Based on industry-standard price per km for pipelines of the assumed capacity
		Pumping station	MDKK	*n/a*	*n/a*	One pumping stations is added for every 200 km of pipeline commenced and one at each end of the offshore pipeline
		Total CAPEX	**MDKK**	**n/a**	**n/a**	
		Acc. OPEX				
		Onshore pipeline fixed O&M	MDKK	*n/a*	*n/a*	Costs are evaluated as 1% of CAPEX per year for the full technical lifetime
		Offshore pipeline fixed O&M	MDKK	*n/a*	*n/a*	Costs are evaluated as 1% of CAPEX per year for the full technical lifetime
		Power	MDKK	*n/a*	*n/a*	Based on 0.5 DKK/KWh pricing
		Total acc. OPEX	**MDKK**	***n/a***	***n/a***	
Total cost/t			**DKK/t**	**106**	**85**	
hereof storage			**DKK/t**	**46**	**41**	
**hereof transport*			**DKK/t**	**60**	**43**	

Other case-specific assumptions:

- Transport pipelines are not included in this set-up
- 50% of German CO2 exports are assumed to come from Rostock (East of Jutland), and the remaining 50% is assumed to come from Hamburg (West of Jutland)
- 100% of exports from NL is assumed to come from Rotterdam harbour

OPTION #2: Onshore, shuttle tanker to Kalundborg harbour and pipeline from Copenhagen to Kalundborg harbour, then to Havnsø via pipeline

Table 52: Overview option #2

	Cost category	Unit	5 MtCO2/y	10 MtCO2/y	Comment
STORAGE	**Pre-Fid**				
	2D seismic	MDKK	*90*	*127*	Based on the size of the area to be assessed
	Baseline studies	MDKK	*20*	*28*	Surveys all relevant pre-injection data
	Appraisal well	MDKK	*55*	*110*	The number of appraisal wells increases linearly with the size of the area to be appraised
	FEED studies	MDKK	*10*	*14*	Front end engineering design
	Approvals	MDKK	*20*	*28*	Regulatory approvals for establishing CO2 storage sites
	Total pre-FID costs	MDKK	**195**	**308**	
	CAPEX				
	Intermediate storage	MDKK	*180*	*180*	Assumed storage size of 50,000 t
	Injection plant	MDKK	*420*	*840*	Includes booster pumps, heat exchangers and boiler system
	Pipeline	MDKK	*140*	*212*	The pipeline between storage and injection site; cost is based on the length and industry-standard per km cost
	Injection wells	MDKK	*1,575*	*3,150*	The number of injection wells scales linearly to accommodate natural injection rate limitations of the storage site
	Wellhead platform	MDKK	*n/a*	*n/a*	The offshore structure that supports injection wells and associated support systems
	Mooring/loading system	MDKK	*n/a*	*n/a*	System for mooring and/or unloading CO2 offshore
	Purpose built CO2 carrier / FSU	MDKK	*n/a*	*n/a*	Permanently moored FSUs near offshore storage site have intermediate storage and injection capabilities
	Total CAPEX	**MDKK**	**2,315**	**4,382**	
	Acc. OPEX				
	Base organisation	MDKK	*175*	*247*	Covers day-to-day operations of the organisation
	Intermediate storage	MDKK	*223*	*223*	Facility size remains constant as additional buffer size does not provide value
	Injection plant	MDKK	*521*	*1,042*	Accumulated variable cost for operating the injection plant systems
	Pipeline	MDKK	*38*	*57*	Costs are evaluated as 1% of CAPEX per year for the full technical lifetime period

		Injection wells	MDKK	*427*	*854*	Accumulated variable cost of operating wells for injection of CO2 into subsurface reservoirs
		Monitoring	MDKK	*670*	*948*	Post-injection monitoring is only evaluated over a 20-year period
		Power	MDKK	*884*	*1,768*	Power scales linearly with the project size and is based on 0.5 DKK/KWh pricing
		Wellhead platform	MDKK	*n/a*	*n/a*	Accumulated variable cost for operating the wellhead platform
		Standby vessel	MDKK	*n/a*	*n/a*	Scales linearly with the number of vessels expected to be near the storage site
		Mooring/loading system	MDKK	*n/a*	*n/a*	Accumulated variable cost for operating the mooring/loading system offshore
		Purpose built CO2 carrier / FSU	MDKK	*n/a*	*n/a*	Accumulated variable cost for operating the FSU offshore
		Total acc. OPEX	**MDKK**	**2,938**	**5,139**	
		Closure costs				
		Abandonment cost	MDKK	*405*	*767*	Evaluated as 17,5% of total storage CAPEX
		Post-Closure cost	MDKK	*400*	*566*	Cost of monitoring the storage site post-closure
		Total closure costs	**MDKK**	**805**	**1,333**	
CO2 TRANSPORT	**Shuttle tanker/ Vessel**	**CAPEX**				
		Transport shuttle	MDKK	*473*	*1,419*	Import via shuttle tankers is assumed to increase from 20% of the import volume to 60% between the 5 and 10 MtCO2/y scenarios
		Vessel	MDKK	*n/a*	*n/a*	Additional cost of equipment for the vessels is included in the CAPEX and OPEX for storage
		Export intermediate storage	MDKK	*2,250*	*2,625*	Total export intermediate storage is 120,000 t and 140,000 t for each scenario, respectively, split between the exporting countries relative to their expected export volume
		Total CAPEX	**MDKK**	**2,723**	**4,044**	
		Acc. OPEX				
		Transport shuttle fixed O&M	MDKK	*2,461*	*4,042*	5% of CAPEX + 75 EUR/ton export intermediate storage per year over the full technical project lifetime
		Vessels fixed O&M	MDKK	*n/a*	*n/a*	5% of CAPEX + 75 EUR/ton export intermediate storage per year over the full technical project lifetime
		Fuel	MDKK	*146*	*875*	Shuttle tankers during transport have been assumed to consume 256 MWh per day, which drives fuel costs
		Total acc. OPEX	**MDKK**	**2,607**	**4,917**	

	Pipeline	**CAPEX**				
		Onshore pipeline	MDKK	*350*	*350*	Normally cost would be 5,3 MDKK/km for 10MT/y, but this is adjusted as the same amount goes through the pipeline from CPH-Kalundborg as in 5Mt/y scenario
		Offshore pipeline	MDKK	*n/a*	*n/a*	Based on industry-standard price per km for pipelines of the assumed capacity
		Pumping station	MDKK	*117*	*117*	One pumping stations is added for every 200 km of pipeline commenced and one at each end of an offshore pipeline
		Total CAPEX	**MDKK**	**467**	**467**	
		Acc. OPEX				
		Onshore pipeline fixed O&M	MDKK	*95*	*95*	Costs are evaluated as 1% of CAPEX per year for the full technical lifetime
		Offshore pipeline fixed O&M	MDKK	*n/a*	*n/a*	Costs are evaluated as 1% of CAPEX per year for the full technical lifetime
		Power	MDKK	*108*	*108*	Based on 0.5 DKK/KWh pricing
		Total acc. OPEX	**MDKK**	**203**	**203**	
Total cost/t			**DKK/t**	**91**	**77**	
***hereof storage**			**DKK/t**	**46**	**41**	
**hereof transport*			**DKK/t**	**44**	**36**	

Other case-specific assumptions:

- A 100 km CO2 transport pipeline from CPH to Kalundborg harbour is included in this set-up carrying 4 MtCO2/y
- Additional import volume between the 5 and 10 MtCO2/y cases is assumed to be transported using only shuttle tankers
- 50% of German CO2 exports are assumed to come from Rostock (East of Jutland), and the remaining 50% is assumed to come from Hamburg (West of Jutland)
- 100% of exports from NL is assumed to come from Rotterdam harbour

OPTION #3: Nearshore, shuttle tanker to Hanstholm harbour, then to Hanstholm storage site via pipeline

Table 53: Overview option #3

	Cost category	Unit	5 MtCO2/y	10 MtCO2/y	Comment
STORAGE	**Pre-Fid**				
	3D seismic	MDKK	*90*	*127*	Based on the size of the area to be assessed
	Baseline studies	MDKK	*20*	*28*	Surveys all relevant pre-injection data
	Appraisal well	MDKK	*230*	*460*	The number of appraisal wells increases linearly with the size of the area to be appraised
	FEED studies	MDKK	*10*	*14*	Front end engineering design
	Approvals	MDKK	*20*	*28*	Regulatory approvals for establishing CO2 storage sites
	Total pre-FID costs	**MDKK**	**370**	**658**	
	CAPEX				
	Intermediate storage	MDKK	*180*	*180*	Assumed storage size of 50,000 t
	Injection plant	MDKK	*420*	*840*	Includes booster pumps, heat exchangers and boiler system
	Pipeline and power cable	MDKK	*350*	*550*	The pipeline between storage and injection site; cost is based on the length and industry-standard per km cost; includes an AC cable providing power to injection operations
	Injection wells	MDKK	*2,835*	*5,670*	The number of injection wells scales linearly to accommodate natural injection rate limitations
	Wellhead platform	MDKK	*280*	*396*	The offshore structure that supports injection wells and associated support systems
	Mooring/loading system	MDKK	*n/a*	*n/a*	System for mooring and/or unloading CO2 offshore
	Purpose built CO2 carrier / FSU	MDKK	*n/a*	*n/a*	Permanently moored FSUs near offshore storage site have intermediate storage and injection capabilities
	Total CAPEX	**MDKK**	**4,065**	**7,636**	
	Acc. OPEX				
	Base organisation	MDKK	*350*	*495*	Covers day-to-day operations of the organisation
	Intermediate storage	MDKK	*223*	*223*	Facility size remains constant as additional buffer size does not provide value
	Injection plant	MDKK	*521*	*1,042*	Accumulated variable cost for operating the injection plant systems
	Pipeline and power cable	MDKK	95	149	Costs are evaluated as a 1% of CAPEX per year for the full technical lifetime period
	Injection wells	MDKK	*825*	*1,650*	Accumulated variable cost of operating wells for injection of CO2 into subsurface reservoirs

		Monitoring	MDKK	*920*	*1,301*	Post-injection monitoring is only evaluated over 20 years
		Power	MDKK	*884*	*1,768*	Power scales linearly with the project size and is based on 0.5 DKK/KWh pricing
		Wellhead platform	MDKK	*694*	*981*	Accumulated variable cost for operating the wellhead platform
		Standby vessel	MDKK	*n/a*	*n/a*	Scales linearly with the number of vessels expected to be near the storage site
		Mooring/loading system	MDKK	*n/a*	*n/a*	Accumulated variable cost for operating the mooring/loading system offshore
		Purpose built CO2 carrier / FSU	MDKK	*n/a*	*n/a*	Accumulated variable cost for operating the FSU offshore
		Total acc. OPEX	**MDKK**	**4,512**	**7,609**	
		Closure costs				
		Abandonment cost	MDKK	*711*	*1,336*	Evaluated as 17,5% of total storage CAPEX
		Post-Closure cost	MDKK	*600*	*849*	Cost of monitoring the storage site post-closure
		Total closure costs	**MDKK**	**1,311**	**2,185**	
CO2 TRANSPORT	**Shuttle tanker/ Vessel**	**CAPEX**				
		Transport shuttle	MDKK	*1,419*	*2,838*	Import via shuttle tankers is assumed to be 100% of the import volume
		Vessel	MDKK	*n/a*	*n/a*	Additional cost of equipment for the vessels is included in the CAPEX and OPEX for storage
		Export intermediate storage	MDKK	*2,250*	*2,625*	Total export intermediate storage is 120,000 t and 140,000 t for each scenario, respectively, split between the exporting countries relative to their expected export volume
		Total CAPEX	**MDKK**	**3,669**	**5,463**	
		Acc. OPEX				
		Transport shuttle fixed O&M	MDKK	*3,738*	*5,958*	5% of CAPEX + 75 EUR/ton export intermediate storage per year over the full technical project lifetime
		Vessels fixed O&M	MDKK	*n/a*	*n/a*	5% of CAPEX + 75 EUR/ton export intermediate storage per year over the full technical project lifetime
		Fuel	MDKK	*761*	*1,522*	Shuttle tankers during transport have been assumed to consume 256 MWh per day, which drives fuel costs
		Total acc. OPEX	**MDKK**	**4,499**	**7,480**	
	Pipeline	**CAPEX**				
		Onshore pipeline	MDKK	*n/a*	*n/a*	Based on industry-standard price per km for pipelines of the assumed capacity

		Offshore pipeline	MDKK	*n/a*	*n/a*	Based on industry-standard price per km for pipelines of the assumed capacity
		Pumping station	MDKK	*n/a*	*n/a*	Shuttle tankers during transport are assumed to consume 256 MWh per day, which drives fuel costs
		Total CAPEX	**MDKK**	**n/a**	**n/a**	
		Acc. OPEX				
		Onshore pipeline fixed O&M	MDKK	*n/a*	*n/a*	Costs are evaluated as 1% of CAPEX per year for the full technical lifetime
		Offshore pipeline fixed O&M	MDKK	*n/a*	*n/a*	Costs are evaluated as 1% of CAPEX per year for the full technical lifetime
		Power	MDKK	*n/a*	*n/a*	Based on 0.5 DKK/KWh pricing
		Total acc. OPEX	**MDKK**	**n/a**	**n/a**	
Total cost/t			**DKK/t**	**136**	**115**	
*****hereof storage*			**DKK/t**	**76**	**67**	
**hereof transport*			**DKK/t**	**61**	**48**	

Other case-specific assumptions:

- Transport pipelines are not included in this set-up
- 50% of German CO2 exports is expected to come from Rostock (East of Jutland), and the remaining 50% is expected to come from Hamburg (West of Jutland)
- 100% of exports from NL is assumed to come from Rotterdam harbour
- Energy is provided to the injection site via an AC electricity cable from the onshore grid to the nearshore injection operations

OPTION #4: Nearshore, shuttle tanker to Hanstholm harbour and pipeline from Copenhagen to Hanstholm harbour, then to Hanstholm storage site via pipeline

Table 54: Overview option #4

	Cost category	Unit	5 MtCO2/y	10 MtCO2/y	Comment
STORAGE	**Pre-Fid**				
	3D seismic	MDKK	*90*	*127*	Based on the size of the area to be assessed
	Baseline studies	MDKK	*20*	*28*	Surveys all relevant pre-injection data
	Appraisal well	MDKK	*230*	*460*	The number of appraisal wells increase linearly with the size of the area to be appraised
	FEED studies	MDKK	*10*	*14*	Front end engineering design
	Approvals	MDKK	*20*	*28*	Regulatory approvals for establishing CO2 storage sites
	Total pre-FID costs	**MDKK**	**370**	**658**	
	CAPEX				
	Intermediate storage	MDKK	*180*	*180*	Assumed storage size of 50,000 t
	Injection plant	MDKK	*420*	*840*	Includes booster pumps, heat exchangers and boiler system
	Pipeline and power cable	MDKK	*350*	*550*	The pipeline between storage and injection site; cost is based on the length and industry-standard per km cost; includes an AC cable providing power to injection operations
	Injection wells	MDKK	*2,835*	*5,670*	The number of injection wells scales linearly to accommodate natural injection rate limitations
	Wellhead platform	MDKK	*280*	*396*	The offshore structure that supports injection wells and associated support systems
	Mooring/loading system	MDKK	*n/a*	*n/a*	System for mooring and/or unloading CO2 offshore
	Purpose built CO2 carrier / FSU	MDKK	*180*	*180*	Permanently moored FSUs near offshore storage site have intermediate storage and injection capabilities
	Total CAPEX	**MDKK**	**4,065**	**7,636**	
	Acc. OPEX				
	Base organisation	MDKK	*350*	*495*	Covers day-to-day operations of the organisation
	Intermediate storage	MDKK	*223*	*223*	Facility size remains constant as additional buffer size does not provide value
	Injection plant	MDKK	*521*	*1,042*	Accumulated variable cost for operating the injection plant systems
	Pipeline and power cable	MDKK	*95*	*149*	Costs are evaluated as 1% of CAPEX per year for the full technical lifetime period
	Injection wells	MDKK	*825*	*1,650*	Accumulated variable cost of operating wells for injection of CO2 into subsurface reservoirs

		Monitoring	MDKK	*920*	*1,301*	Post-injection monitoring is only evaluated over a 20-year period
		Power	MDKK	*884*	*1,768*	Power scales linearly with the project size and is based on 0.5 DKK/KWh pricing
		Wellhead platform	MDKK	*694*	*981*	Accumulated variable cost for operating the wellhead platform
		Standby vessel	MDKK	*n/a*	*n/a*	Scales linearly with the number of vessels expected to be near the storage site
		Mooring/loading system	MDKK	*n/a*	*n/a*	Accumulated variable cost for operating the mooring/loading system offshore
		Purpose built CO2 carrier / FSU	MDKK	*n/a*	*n/a*	Accumulated variable cost for operating the FSU offshore
		Total CAPEX	**MDKK**	**4,512**	**7,609**	
		Closure costs				
		Abandonment cost	MDKK	*711*	*1,336*	Evaluated as 17,5% of total storage CAPEX
		Post-Closure cost	MDKK	*600*	*849*	Cost of monitoring the storage site post-closure
		Total closure costs	**MDKK**	**1,311**	**2,185**	
CO2 TRANSPORT	**Shuttle tanker/ Vessel**	**CAPEX**				
		Transport shuttle	MDKK	*473*	*1,892*	Import via shuttle tankers is assumed to increase from 20% of the import volume to 60% between the 5 and 10 MtCO2/y scenarios
		Vessel	MDKK	*n/a*	*n/a*	The additional cost of equipment for the vessels is included in the CAPEX and OPEX for storage
		Export intermediate storage	MDKK	*1,875*	*2,063*	Total export intermediate storage is 100,000 t and 110,000 t for each scenario, respectively, split between the exporting countries relative to their expected export volume
		Total CAPEX	**MDKK**	**2,348**	**3,955**	
		Acc. OPEX	MDKK			
		Transport shuttle fixed O&M	MDKK	*2,157*	*4,225*	5% of CAPEX + 75 EUR/ton export intermediate storage per year over the full technical project lifetime
		Vessels fixed O&M	MDKK	*n/a*	*n/a*	5% of CAPEX + 75 EUR/ton export intermediate storage per year over the full technical project lifetime
		Fuel	MDKK	*159*	*952*	Shuttle tankers during transport have been assumed to consume 256 MWh per day, which drives fuel costs
		Total acc. OPEX	**MDKK**	**2,316**	**5,177**	

	Pipeline	**CAPEX**				
		Onshore pipeline	MDKK	*1,050*	*1,050*	Cost of pipeline from CPH to Hanstholm is split into two parts, onshore part and offshore part; throughput of 4 MtCO2/y is assumed the same for both scenarios meaning no change in price
		Offshore pipeline	MDKK	*700*	*700*	
		Pumping station	MDKK	*350*	*350*	One pumping stations is added for every 200 km of pipeline commenced and one at each end of an offshore pipeline
		Total CAPEX	**MDKK**	**2,100**	**2,100**	
		Acc. OPEX				
		Onshore pipeline fixed O&M	MDKK	*284*	*284*	Costs are evaluated as 1% of CAPEX per year for the full technical lifetime
		Offshore pipeline fixed O&M	MDKK	*189*	*297*	Costs are evaluated as 1% of CAPEX per year for the full technical lifetime
		Power	MDKK	*432*	*432*	Based on 0.5 DKK/KWh pricing
		Total acc. OPEX	**MDKK**	**905**	**1,013**	
Total cost/t			**DKK/t**	**133**	**112**	
***hereof storage**			**DKK/t**	**76**	**67**	
***hereof transport**			**DKK/t**	**57**	**45**	

Other case-specific assumptions:

- A 400 km CO2 transport pipeline from CPH to Hanstholm harbour is included in this set-up, consisting of 300 km onshore pipeline and 100 km offshore pipeline, assumed to transport 4 MtCO2/y for both the 5 and 10 MtCO2/y scenarios. Additional import volume for the 5 and 10 MtCO2/y scenarios is assumed to be transported from emission sources to Hanstholm harbour using shuttle tankers
- 50% of German CO2 exports are assumed to come from Rostock (East of Jutland), and the remaining 50% is assumed to come from Hamburg (West of Jutland)
- 100% of exports from NL is assumed to come from Rotterdam harbour
- Energy is provided to the injection site via an AC electricity cable from the onshore grid to the nearshore injection operations

OPTION #5: Offshore, shuttle tanker to Esbjerg harbour, then to the North Sea offshore storage site via pipeline

Table 55: Overview option #5

		Cost category	Unit	5 MtCO2/y	10 MtCO2/y	Comment
STORAGE		**Pre-Fid**				
		3D seismic	MDKK	*70*	*99*	Based on the size of the area to be assessed
		Baseline studies	MDKK	*20*	*28*	Surveys all relevant pre-injection data
		Appraisal well	MDKK	*n/a*	*n/a*	Appraisal wells are not included as the geological structures of the offshore storage sites are assumed to be well known due to prior mapping by the oil and gas industry
		FEED studies	MDKK	*10*	*14*	Front end engineering design
		Approvals	MDKK	*20*	*28*	Regulatory approvals for establishing CO2 storage sites
		Total pre-FID costs	**MDKK**	**120**	**170**	
		CAPEX				
		Intermediate storage	MDKK	*180*	*180*	Assumed storage size of 50,000 t
		Injection plant	MDKK	*390*	*780*	Includes booster pumps, heat exchangers and boiler system
		Pipeline	MDKK	*1,750*	*2,750*	The pipeline between storage and injection site; does not include the cost of electricity cable; cost is based on the length and industry-standard per km cost
		Injection wells	MDKK	*1,925*	*3,850*	The number of injection wells scales linearly to accommodate natural injection rate limitations
		Wellhead platform	MDKK	*525*	*742*	The offshore structure that supports injection wells and associated support systems
		Mooring/loading system	MDKK	*n/a*	*n/a*	System for mooring and/or unloading CO2 offshore
		Purpose built CO2 carrier / FSU	MDKK	*n/a*	*n/a*	Permanently moored FSUs near offshore storage site have intermediate storage and injection capabilities
		Total CAPEX	**MDKK**	**4,770**	**8,302**	
		Acc. OPEX				
		Base organisation	MDKK	*525*	*742*	Covers day-to-day operations of the organisation
		Intermediate storage	MDKK	*223*	*223*	Facility size remains constant as additional buffer size does not provide value
		Injection plant	MDKK	*967*	*1,934*	Accumulated variable cost for operating the injection plant systems
		Pipeline	MDKK	*473*	*743*	Costs are evaluated as 1% of CAPEX per year for the full technical lifetime period

		Injection wells	MDKK	*527*	*1,054*	Accumulated variable cost of operating wells for injection of CO2 into subsurface reservoirs
		Monitoring	MDKK	*920*	*1,301*	Post-injection monitoring is only evaluated over 20 years
		Power	MDKK	*3,036*	*6,072*	Power scales linearly with the project size and is based on 0.5 DKK/KWh pricing
		Wellhead platform	MDKK	*2,430*	*3,437*	Accumulated variable cost for operating the wellhead platform
		Standby vessel	MDKK	*n/a*	*n/a*	Scales linearly with the number of vessels expected to be near the storage site
		Mooring/loading system	MDKK	*n/a*	*n/a*	Accumulated variable cost for operating the mooring/loading system offshore
		Purpose built CO2 carrier / FSU	MDKK	*n/a*	*n/a*	Accumulated variable cost for operating the FSU offshore
		Total CAPEX	**MDKK**	**9,101**	**15,506**	
		Closure costs				
		Abandonment cost	MDKK	*835*	*1,453*	Evaluated as 17,5% of total storage CAPEX
		Post-Closure cost	MDKK	*600*	*849*	Cost of monitoring the storage site post-closure
		Total closure costs	**MDKK**	**1,435**	**2,301**	
CO2 TRANSPORT	**Shuttle tanker/ Vessel**	**CAPEX**				
		Transport shuttle	MDKK	*1,419*	*2,838*	Import via shuttle tankers is assumed to be 100% of the import volume
		Vessel	MDKK	*n/a*	*n/a*	Additional cost of equipment for the vessels is included in the CAPEX and OPEX for storage
		Export intermediate storage	MDKK	*2,250*	*2,625*	Total export intermediate storage is 120,000 t and 140,000 t for each scenario, respectively, split between the exporting countries relative to their expected export volume
		Total CAPEX	**MDKK**	**3,669**	**5,463**	
		Acc. OPEX	MDKK			
		Transport shuttle fixed O&M	MDKK	*3,738*	*5,958*	5% of CAPEX + 75 EUR/ton export intermediate storage per year over the full technical project lifetime
		Vessels fixed O&M	MDKK	*n/a*	*n/a*	5% of CAPEX + 75 EUR/ton export intermediate storage per year over the full technical project lifetime
		Fuel	MDKK	*848*	*1,697*	Shuttle tankers during transport are assumed to consume 256 MWh per day, which drives fuel costs
		Total acc. OPEX	**MDKK**	**4,587**	**7,655**	

	Pipeline	**CAPEX**				
		Onshore pipeline	MDKK	*n/a*	*n/a*	Based on industry-standard price per km for pipelines of the assumed capacity
		Offshore pipeline	MDKK	*n/a*	*n/a*	Based on industry-standard price per km for pipelines of the assumed capacity
		Pumping station	MDKK	*n/a*	*n/a*	One pumping stations is added for every 200 km of pipeline commenced and 1 at each end of the offshore pipeline
		Total CAPEX	**MDKK**	**n/a**	**n/a**	
		Acc. OPEX				
		Onshore pipeline fixed O&M	MDKK	*n/a*	*n/a*	Costs are evaluated as 1% of CAPEX per year for the full technical lifetime
		Offshore pipeline fixed O&M	MDKK	*n/a*	*n/a*	Costs are evaluated as 1% of CAPEX per year for the full technical lifetime
		Power	MDKK	*n/a*	*n/a*	Based on 0.5 DKK/KWh pricing
		Total acc. OPEX	**MDKK**	**n/a**	**n/a**	
Total cost/t			**DKK/t**	**175**	**146**	
***hereof storage**			**DKK/t**	**114**	**97**	
**hereof transport*			**DKK/t**	**61**	**49**	

Other case-specific assumptions:

- Transport pipelines are not included in this set-up
- 50% of German CO2 exports are assumed to come from Rostock (East of Jutland), and the remaining 50% is assumed to come from Hamburg (West of Jutland)
- 100% of exports from NL is assumed to come from Rotterdam harbour
- Infrastructure for providing energy offshore is assumed to already be installed and has not been included in the above estimates
- Injection wells are placed in the Northern part of the North Sea oil and gas fields as the geological structure of these sites means fewer wells are needed for the same injection rate compared to the remaining Danish oil and gas fields

OPTION #6: Offshore, vessel to North Sea offshore storage site, then direct injection of CO2 into storage site using onboard equipment

Table 56: Overview option #6

		Cost category	Unit	5 MtCO2/y	10 MtCO2/y	Comment
STORAGE		**Pre-Fid**				
		3D seismic	MDKK	*150*	*250*	Based on the size of the area to be assessed
		Baseline studies	MDKK	*60*	*100*	Surveys all relevant pre-injection data
		Appraisal well	MDKK	*n/a*	*n/a*	Appraisal wells are not included as the geological structures of the offshore storage sites are assumed to be well known due to prior mapping by the oil and gas industry
		FEED studies	MDKK	*30*	*50*	Front end engineering design
		Approvals	MDKK	*60*	*100*	Regulatory approvals for establishing CO2 storage sites
		Total pre-FID costs	**MDKK**	**300**	**500**	
		CAPEX				
		Intermediate storage	MDKK	*n/a*	*n/a*	Intermediate storage is included in the cost of the vessel
		Injection plant	MDKK	*340*	*680*	Includes booster pumps, heat exchangers and boiler system
		Pipeline	MDKK	*n/a*	*n/a*	Pipeline between storage and injection site; does not include cost of electricity cable; cost is based on length and industry-standard per km cost
		Injection wells	MDKK	*1,960*	*3,920*	Number of injection wells scale linearly to accommodate natural injection rate limitations
		Wellhead platform	MDKK	*275*	*550*	The offshore structure that supports injection wells and associated support systems
		Mooring/loading system	MDKK	*405*	*675*	Includes a SAL system allowing vessels to attach themselves to wells and start injection of the transported CO2
		Purpose built CO2 carrier / FSU	MDKK	*n/a*	*n/a*	Permanently moored FSUs near offshore storage site have intermediate storage and injection capabilities
		Total CAPEX	**MDKK**	**2,980**	**5,825**	
		Acc. OPEX				
		Base organisation	MDKK	*525*	*525*	Covers day-to-day operations of the organisation
		Intermediate storage	MDKK	*n/a*	*n/a*	Facility size remains constant as additional buffer size does not provide value
		Injection plant	MDKK	*844*	*1.688*	Accumulated variable cost for operating the injection plant systems

		Pipeline	MDKK	*n/a*	*n/a*	Costs are evaluated as 1% of CAPEX per year for the full technical lifetime period
		Injection wells	MDKK	*608*	*1.216*	Accumulated variable cost of operating wells for injection of CO2 into subsurface reservoirs
		Monitoring	MDKK	*920*	*1.840*	Post-injection monitoring is only evaluated over 20 years
		Power	MDKK	*3,450*	*6,900*	Power scales linearly with the project size and is based on 0.5 DKK/KWh pricing
		Wellhead platform	MDKK	*4,650*	*9,300*	Accumulated variable cost for operating the wellhead platform
		Standby vessel	MDKK	*1,240*	*2,480*	Scales linearly with the number of vessels expected to be near the storage site
		Mooring/loading system	MDKK	*1,005*	*1,675*	Accumulated variable cost for operating the mooring/loading system offshore
		Purpose built CO2 carrier / FSU	MDKK	*n/a*	*n/a*	Accumulated variable cost for operating the FSU offshore
		Total CAPEX	**MDKK**	**13,242**	**25,624**	
		Closure costs				
		Abandonment cost	MDKK	*522*	*1,019*	Evaluated as 17,5% of total storage CAPEX
		Post-Closure cost	MDKK	*600*	*849*	Cost of monitoring the storage site post-closure
		Total closure costs	**MDKK**	**1,122**	**1,868**	
CO2 TRANSPORT	**Shuttle tanker/ Vessel**	**CAPEX**				
		Transport shuttle	MDKK	*n/a*	*n/a*	Import via shuttle tankers is assumed to be 0% of the import volume
		Vessel	MDKK	*2,292*	*4,584*	Import via vessels is assumed to be 100% of the import volume; the additional cost of equipment for the vessels is included in the CAPEX and OPEX for storage
		Export intermediate storage	MDKK	*2,250*	*2,625*	Total export intermediate storage is 120,000 t and 140,000 t for each scenario, respectively, split between the exporting countries relative to their expected export volume
		Total CAPEX	**MDKK**	**4,542**	**7,209**	
		Acc. OPEX	MDKK			
		Transport shuttle fixed O&M	MDKK	*n/a*	*n/a*	5% of CAPEX + 75 EUR/ton export intermediate storage per year over the full technical project lifetime
		Vessels fixed O&M	MDKK	*4,917*	*8,315*	5% of CAPEX + 75 EUR/ton export intermediate storage per year over the full technical project lifetime
		Fuel	MDKK	*843*	*1,686*	Shuttle tankers during transport are assumed to consume 256

						MWh per day, which drives fuel costs
		Total acc. OPEX	**MDKK**	**5,759**	**10,000**	
	Pipeline	**CAPEX**				
		Onshore pipeline	MDKK	*n/a*	*n/a*	Based on industry-standard price per km for pipelines of the assumed capacity
		Offshore pipeline	MDKK	*n/a*	*n/a*	Based on industry-standard price per km for pipelines of the assumed capacity
		Pumping station	MDKK	*n/a*	*n/a*	One pumping stations is added for every 200 km of pipeline commenced and one at each end of the offshore pipeline
		Total CAPEX	**MDKK**	**n/a**	**n/a**	
		Acc. OPEX				
		Onshore pipeline fixed O&M	MDKK	*n/a*	*n/a*	Costs are evaluated as 1% of CAPEX per year for the full technical lifetime
		Offshore pipeline fixed O&M	MDKK	*n/a*	*n/a*	Costs are evaluated as 1% of CAPEX per year for the full technical lifetime
		Power	MDKK	*n/a*	*n/a*	Based on 0.5 DKK/KWh pricing
		Total acc. OPEX	**MDKK**	**n/a**	**n/a**	
Total cost/t			**DKK/t**	**207**	**189**	
*****_hereof storage_			**DKK/t**	**131**	**125**	
**hereof transport*			**DKK/t**	**76**	**64**	

Other case-specific assumptions:

- Transport pipelines are not included in this set-up
- All transport of CO2 happens via vessels with onboard intermediate storage and injection capabilities, meaning no intermediate storage near the storage site is needed for the set-up
- 50% of German CO2 exports are assumed to come from Rostock (East of Jutland), and the remaining 50% is assumed to come from Hamburg (West of Jutland)
- 100% of exports from NL is assumed to come from Rotterdam harbour
- Appraisal wells are not included as the geological structures of the offshore storage sites are assumed to be well known due to prior mapping by the oil and gas industry
- Infrastructure for providing energy offshore is assumed to be already installed and has not been included in the above estimates
- Injection wells are placed at five different injection clusters with two platforms at each cluster. The clusters will be found in the Northern part of the North Sea oil and gas fields as the geological structure of these sites means fewer wells are needed for the same injection rate compared to the remaining Danish oil and gas fields
- The cost of pipelines between the clusters has not been included as no pre-existing cost estimates have been found. Construction of these pipelines might be necessary if this set-up structure will be used as the.
- This set-up is the most expensive due to increased cost for Wellhead platform, standby vessels, mooring/loading system, CAPEX and OPEX for vessels, which is caused by a decrease in utilisation rate and increase in loading/unloading time per cycle

OPTION #7: Offshore, shuttle tanker to offshore FSU near North Sea storage site, then to North Sea storage site using FSU onboard injection equipment

Table 57: Overview option #7

		Cost category	Unit	5 MtCO2/y	10 MtCO2/y	Comment
STORAGE		**Pre-Fid**				
		3D seismic	MDKK	*70*	*99*	Based on the size of the area to be assessed
		Baseline studies	MDKK	*20*	*28*	Surveys all relevant pre-injection data
		Appraisal well	MDKK	*n/a*	*n/a*	Appraisal wells are not included as the geological structures of the offshore storage sites are assumed to be well known due to prior mapping by the oil and gas industry
		FEED studies	MDKK	*10*	*14*	Front end engineering design
		Approvals	MDKK	*20*	*28*	Regulatory approvals for establishing CO2 storage sites
		Total pre-FID costs	**MDKK**	**120**	**170**	
		CAPEX				
		Intermediate storage	MDKK	*n/a*	*n/a*	Intermediate storage is included in the cost of the FSU
		Injection plant	MDKK	*390*	*780*	Includes booster pumps, heat exchangers and boiler system
		Pipeline	MDKK	*n/a*	*n/a*	Pipeline between storage and injection site; does not include cost of electricity cable; cost is based on length and industry-standard per km cost
		Injection wells	MDKK	*1,925*	*3,850*	Number of injection wells scale linearly to accommodate natural injection rate limitations
		Wellhead platform	MDKK	*525*	*742*	Offshore structure that supports injection wells and associated support systems
		Mooring/loading system	MDKK	*375*	*530*	The estimated cost is based on industry standards from the oil and gas industry
		Purpose built CO2 carrier / FSU	MDKK	*640*	*905*	Permanently moored FSUs near offshore storage site have intermediate storage and injection capabilities
		Total CAPEX	**MDKK**	**3,855**	**6,808**	
		Acc. OPEX				
		Base organisation	MDKK	*525*	*742*	Covers day-to-day operations of the organisation
		Intermediate storage	MDKK	*n/a*	*n/a*	Facility size remains constant as additional buffer size does not provide value
		Injection plant	MDKK	*967*	*1,934*	Accumulated variable cost for operating the injection plant systems

		Pipeline	MDKK	*n/a*	*n/a*	Costs are evaluated as 1% of CAPEX per year for the full technical lifetime period
		Injection wells	MDKK	*527*	*1,054*	Accumulated variable cost of operating wells for injection of CO2 into subsurface reservoirs
		Monitoring	MDKK	*920*	*1,301*	Post-injection monitoring is only evaluated over 20 years
		Power	MDKK	*3,036*	*6,072*	Power scales linearly with the project size and is based on 0.5 DKK/KWh pricing
		Wellhead platform	MDKK	*2,430*	*3,437*	Accumulated variable cost for operating the wellhead platform
		Standby vessel	MDKK	*620*	*1,240*	Scales linearly with the number of vessels expected to be near the storage site
		Mooring/loading system	MDKK	*831*	*1,662*	Accumulated variable cost for operating the mooring/loading system offshore
		Purpose built CO2 carrier / FSU	MDKK	*1,587*	*2,244*	Accumulated variable cost for operating the FSU offshore
		Total CAPEX	**MDKK**	**11,443**	**19,686**	
		Closure costs				
		Abandonment cost	MDKK	*675*	*1,191*	Evaluated as 17,5% of total storage CAPEX
		Post-Closure cost	MDKK	*600*	*849*	Cost of monitoring the storage site post-closure
		Total closure costs	**MDKK**	**1,275**	**2,040**	
CO2 TRANSPORT	**Shuttle tanker/ Vessel**	**CAPEX**				
		Transport shuttle	MDKK	*1,419*	*2,838*	Import via shuttle tankers is assumed to be 100% of the import volume unloading at an FSU near the storage site
		Vessel	MDKK	*n/a*	*n/a*	The additional cost of equipment for the vessels is included in the CAPEX and OPEX for storage
		Export intermediate storage	MDKK	*2,250*	*2,625*	Total export intermediate storage is 120,000 t and 140,000 t for each scenario, respectively, split between the exporting countries relative to their expected export volume
		Total CAPEX	**MDKK**	**3,669**	**5,463**	
		Acc. OPEX				
		Transport shuttle fixed O&M	MDKK	*3,738*	*5,958*	5% of CAPEX + 75 EUR/ton export intermediate storage per year over the full technical project lifetime
		Vessels fixed O&M	MDKK	*n/a*	*n/a*	5% of CAPEX + 75 EUR/ton export intermediate storage per year over the full technical project lifetime
		Fuel	MDKK	*837*	*1,675*	Shuttle tankers during transport are assumed to consume 256 MWh per day, which drives fuel costs

		Total acc. OPEX	**MDKK**	**4,575**	**7,632**	
	Pipeline	**CAPEX**				
		Onshore pipeline	MDKK	*n/a*	*n/a*	Based on industry-standard price per km for pipelines of the assumed capacity
		Offshore pipeline	MDKK	*n/a*	*n/a*	Based on industry-standard price per km for pipelines of the assumed capacity
		Pumping station	MDKK	*n/a*	*n/a*	One pumping stations is added for every 200 km of pipeline commenced and one at each end of the offshore pipeline
		Total CAPEX	**MDKK**	**n/a**	**n/a**	
		Acc. OPEX				
		Onshore pipeline fixed O&M	MDKK	*n/a*	*n/a*	Costs are evaluated as 1% of CAPEX per year for the full technical lifetime
		Offshore pipeline fixed O&M	MDKK	*n/a*	*n/a*	Costs are evaluated as 1% of CAPEX per year for the full technical lifetime
		Power	MDKK	*n/a*	*n/a*	Based on 0.5 DKK/KWh pricing
		Total acc. OPEX	**MDKK**	**n/a**	**n/a**	
Total cost/t			**DKK/t**	**185**	**155**	
hereof storage			**DKK/t**	**124**	**106**	
**hereof transport*			**DKK/t**	**61**	**49**	

- Transport pipelines are not included in this set-up
- All transport of CO2 happens via transport shuttles which unload to a permanent floating storage unit (FSU) with intermediate storage and injection capabilities near offshore storage sites
- 50% of German CO2 exports are assumed to come from Rostock (East of Jutland), and the remaining 50% is assumed to come from Hamburg (West of Jutland)
- 100% of exports from NL is assumed to come from Rotterdam harbour
- Appraisal wells are not included as the geological structures of the offshore storage sites are assumed to be well known due to prior mapping by the oil and gas industry
- Infrastructure for providing energy offshore is assumed to already be installed and has not been included in the above estimates
- Injection wells are placed in the Northern part of the North Sea oil and gas fields as the geological structure of these sites means fewer wells are needed for the same injection rate compared to the remaining Danish oil and gas fields

OPTION #8: Offshore, shuttle tanker to Esbjerg harbour and pipeline from Hamburg to Esbjerg harbour, then to the storage site via pipeline

Table 58: Overview option #8

		Cost category	Unit	5 $MtCO_2/y$	10 $MtCO_2/y$	Comment
STORAGE		**Pre-Fid**				
		3D seismic	MDKK	*70*	*99*	Based on the size of the area to be assessed
		Baseline studies	MDKK	*20*	*28*	Surveys all relevant pre-injection data
		Appraisal well	MDKK	*n/a*	*n/a*	Appraisal wells are not included as the geological structures of the offshore storage sites are assumed to be well known due to prior mapping by the oil and gas industry
		FEED studies	MDKK	*10*	*14*	Front end engineering design
		Approvals	MDKK	*20*	*28*	Regulatory approvals for establishing CO2 storage sites
		Total pre-FID costs	**MDKK**	**120**	**170**	
		CAPEX				
		Intermediate storage	MDKK	*180*	*180*	Assumed storage size of 50,000 t
		Injection plant	MDKK	*390*	*780*	Includes booster pumps, heat exchangers and boiler system
		Pipeline	MDKK	*1,750*	*2,750*	Pipeline between storage and injection site; does not include the cost of electricity cable; cost is based on length and industry-standard per km cost
		Injection wells	MDKK	*1,925*	*3,850*	Number of injection wells scale linearly to accommodate natural injection rate limitations
		Wellhead platform	MDKK	*525*	*742*	The offshore structure that supports injection wells and associated support systems
		Mooring/loading system	MDKK	*n/a*	*n/a*	The estimated cost is based on industry standards from the oil and gas industry
		Purpose built CO2 carrier / FSU	MDKK	*n/a*	*n/a*	Permanently moored FSUs near offshore storage site have intermediate storage and injection capabilities
		Total CAPEX	**MDKK**	**4,770**	**8,302**	
		Acc. OPEX				
		Base organisation	MDKK	*525*	*742*	Covers day-to-day operations of the organisation
		Intermediate storage	MDKK	*223*	*223*	Facility size remains constant as additional buffer size does not provide value
		Injection plant	MDKK	*967*	*1,934*	Accumulated variable cost for operating the injection plant systems
		Pipeline	MDKK	*473*	*743*	Costs are evaluated as 1% of CAPEX per year for the full technical lifetime period

		Injection wells	MDKK	*527*	*1,054*	Accumulated variable cost of operating wells for injection of CO2 into subsurface reservoirs
		Monitoring	MDKK	*920*	*1,301*	Post-injection monitoring is only evaluated over 20 years
		Power	MDKK	*3,036*	*6,072*	Power scales linearly with the project size and is based on 0.5 DKK/KWh pricing
		Wellhead platform	MDKK	*2,430*	*3,437*	Accumulated variable cost for operating the wellhead platform
		Standby vessel	MDKK	*n/a*	*n/a*	Scales linearly with the number of vessels expected to be near the storage site
		Mooring/loading system	MDKK	*n/a*	*n/a*	Accumulated variable cost for operating the mooring/loading system offshore
		Purpose built CO2 carrier / FSU	MDKK	*n/a*	*n/a*	Accumulated variable cost for operating the FSU offshore
		Total CAPEX	**MDKK**	**9,101**	**15,506**	
		Closure costs				
		Abandonment cost	MDKK	*835*	*1,453*	Evaluated as 17,5% of total storage CAPEX
		Post-Closure cost	MDKK	*600*	*849*	Cost of monitoring the storage site post-closure
		Total closure costs	**MDKK**	**1,435**	**2,301**	
CO2 TRANSPORT	**Shuttle tanker/ Vessel**	**CAPEX**				
		Transport shuttle	MDKK	*473*	*1,419*	Import via shuttle tankers is assumed to increase from 20% of the import volume to 50% between the 5 and 10 MtCO2/y scenarios
		Vessel	MDKK	*n/a*	*n/a*	The additional cost of equipment for the vessels is included in the CAPEX and OPEX for storage
		Export intermediate storage	MDKK	*2,250*	*2,625*	Total export intermediate storage is 120,000 t and 140,000 t for each scenario, respectively, split between the exporting countries relative to their expected export volume
		Total CAPEX	**MDKK**	**2,723**	**4,517**	
		Acc. OPEX	MDKK			
		Transport shuttle fixed O&M	MDKK	*2,461*	*4,680*	5% of CAPEX + 75 EUR/ton export intermediate storage per year over the full technical project lifetime
		Vessels fixed O&M	MDKK	*n/a*	*n/a*	5% of CAPEX + 75 EUR/ton export intermediate storage per year over the full technical project lifetime
		Fuel	MDKK	*198*	*991*	Shuttle tankers during transport are assumed to consume 256 MWh per day, which drives fuel costs
		Total acc. OPEX	**MDKK**	**2,659**	**5,672**	

	Pipeline	**CAPEX**				
		Onshore pipeline	MDKK	*875*	*1,325*	Based on industry-standard price per km for pipelines of the assumed capacity
		Offshore pipeline	MDKK	*n/a*	*n/a*	Based on industry-standard price per km for pipelines of the assumed capacity
		Pumping station	MDKK	*233*	*233*	One pumping stations is added for every 200 km of pipeline commenced and one at each end of the offshore pipeline
		Total CAPEX	**MDKK**	**506**	**695**	
		Acc. OPEX				
		Onshore pipeline fixed O&M	MDKK	*236*	*358*	Costs are evaluated as 1% of CAPEX per year for the full technical lifetime
		Offshore pipeline fixed O&M	MDKK	*n/a*	*n/a*	Costs are evaluated as 1% of CAPEX per year for the full technical lifetime
		Power	MDKK	*270*	*338*	Based on 0.5 DKK/KWh pricing
		Total acc. OPEX	**MDKK**	**506**	**695**	
Total cost/t			**DKK/t**	**166**	**139**	
hereof storage			**DKK/t**	**114**	**97**	
**hereof transport*			**DKK/t**	**52**	**42**	

Other case-specific assumptions:

- A 250 km CO2 transport pipeline from Hamburg to Esbjerg harbour is included in this set-up carrying 4 MtCO2/y in the 5 MtCO2/y scenarios and 5 MtCO2/y in the 10 MtCO2/y scenarios. Additional imported CO2 volume between the 5 and 10 MtCO2/y scenarios is assumed to be transported from the emission source to Esbjerg harbour using shuttle tankers
- 50% of German CO2 exports is expected to come from Rostock (East of Jutland), and the remaining 50% is expected to come from Hamburg (West of Jutland)
- 100% of exports from NL is assumed to come from Rotterdam harbour
- Appraisal wells are not included as the geological structures of the offshore storage sites are assumed to be well known due to prior mapping by the oil and gas industry
- Infrastructure for providing energy offshore is assumed to already be installed and has not been included in the above estimates
- Injection wells are placed in the Northern part of the North Sea oil and gas fields as the geological structure of these sites means fewer wells are needed for the same injection rate compared to the remaining Danish oil and gas fields

OPTION #9: Offshore, shuttle tanker to Esbjerg harbour, then to the storage site via pipeline and two separate pipelines from Hamburg and Rotterdam to North Sea storage site

Table 59: Overview option #9

		Cost category	Unit	5 $MtCO_2/y$	10 $MtCO_2/y$	Comment
STORAGE		**Pre-Fid**				
		3D seismic	MDKK	*70*	*99*	Based on the size of the area to be assessed
		Baseline studies	MDKK	*20*	*28*	Surveys all relevant pre-injection data
		Appraisal well	MDKK	*n/a*	*n/a*	Appraisal wells are not included as the geological structures of the offshore storage sites are assumed to be well known due to prior mapping by the oil and gas industry
		FEED studies	MDKK	*10*	*14*	Front end engineering design
		Approvals	MDKK	*20*	*28*	Regulatory approvals for establishing CO2 storage sites
		Total pre-FID costs	**MDKK**	**120**	**170**	
		CAPEX				
		Intermediate storage	MDKK	*180*	*180*	Assumed storage size of 50,000 t
		Injection plant	MDKK	*390*	*780*	Includes booster pumps, heat exchangers and boiler system
		Pipeline	MDKK	*1,750*	*2,750*	Pipeline between storage and injection site; does not include cost of electricity cable; cost is based on length and industry-standard per km cost
		Injection wells	MDKK	*1,925*	*3,850*	Number of injection wells scales linearly to accommodate natural injection rate limitations
		Wellhead platform	MDKK	*525*	*742*	Offshore structure that supports injection wells and associated support systems
		Mooring/loading system	MDKK	*n/a*	*n/a*	The estimated cost is based on industry standards from the oil and gas industry
		Purpose built CO2 carrier / FSU	MDKK	*n/a*	*n/a*	Permanently moored FSUs near offshore storage site have intermediate storage and injection capabilities
		Total CAPEX	**MDKK**	**4,770**	**8,302**	
		Acc. OPEX				
		Base organisation	MDKK	*525*	*742*	Covers day-to-day operations of the organisation
		Intermediate storage	MDKK	*223*	*223*	Facility size remains constant as additional buffer size does not provide value
		Injection plant	MDKK	*967*	*1,934*	Accumulated variable cost for operating the injection plant systems

		Pipeline	MDKK	*473*	*743*	Costs are evaluated as 1% of CAPEX per year for the full technical lifetime period
		Injection wells	MDKK	*527*	*1,054*	Accumulated variable cost of operating wells for injection of CO2 into subsurface reservoirs
		Monitoring	MDKK	*920*	*1,301*	Post-injection monitoring is only evaluated over 20 years
		Power	MDKK	*3,036*	*6,072*	Power scales linearly with the project size and is based on 0.5 DKK/KWh pricing
		Wellhead platform	MDKK	*2,430*	*3,437*	Accumulated variable cost for operating the wellhead platform
		Standby vessel	MDKK	*n/a*	*n/a*	Scales linearly with the number of vessels expected to be near the storage site
		Mooring/loading system	MDKK	*n/a*	*n/a*	Accumulated variable cost for operating the mooring/loading system offshore
		Purpose built CO2 carrier / FSU	MDKK	*n/a*	*n/a*	Accumulated variable cost for operating the FSU offshore
		Total CAPEX	**MDKK**	**9,101**	**15,506**	
		Closure costs				
		Abandonment cost	MDKK	*835*	*1,453*	Evaluated as 17,5% of total storage CAPEX
		Post-Closure cost	MDKK	*600*	*849*	Cost of monitoring the storage site post-closure
		Total closure costs	**MDKK**	**1,435**	**2,301**	
CO2 TRANSPORT	**Shuttle tanker/ Vessel**	**CAPEX**				
		Transport shuttle	MDKK	*473*	*1,419*	Import via shuttle tankers is assumed to decrease from 80% of the import volume to 60% between the 5 and 10 MtCO2/y scenarios
		Vessel	MDKK	*n/a*	*n/a*	Additional cost of equipment for the vessels is included in the CAPEX and OPEX for storage
		Export intermediate storage	MDKK	*2,250*	*2,625*	Total export intermediate storage is 120,000 t and 140,000 t for each scenario, respectively, split between the exporting countries relative to their expected export volume
		Total CAPEX	**MDKK**	**2,723**	**4,044**	
		Acc. OPEX	MDKK			
		Transport shuttle fixed O&M	MDKK	*2,461*	*4,042*	5% of CAPEX + 75 EUR/ton export intermediate storage per year over the full technical project lifetime
		Vessels fixed O&M	MDKK	*n/a*	*n/a*	5% of CAPEX + 75 EUR/ton export intermediate storage per year over the full technical project lifetime
		Fuel	MDKK	*207*	*827*	Shuttle tankers during transport are assumed to consume 256 MWh per day, which drives fuel costs

		Total acc. OPEX	**MDKK**	**2,668**	**4,869**	
	Pipeline	**CAPEX**				
		Onshore pipeline	MDKK	*n/a*	*n/a*	Based on industry-standard price per km for pipelines of the assumed capacity
		Offshore pipeline	MDKK	*5,950*	*5,950*	The offshore pipeline is a combination of the Hamburg and Rotterdam pipelines, both transporting CO2 directly to the North Sea storage sites; does not include electricity cable cost; pipelines with the same capacity is assumed to be used in both scenarios causing cost to stay the same
		Pumping station	MDKK	*467*	*467*	One pumping stations is added for every 200 km of pipeline commenced and one at each end of the offshore pipelines; it does not include electricity cable cost
		Total CAPEX	**MDKK**	**6,417**	**6,417**	
		Acc. OPEX				
		Onshore pipeline fixed O&M	MDKK	*n/a*	*n/a*	Costs are evaluated as 1% of CAPEX per year for the full technical lifetime
		Offshore pipeline fixed O&M	MDKK	*1,607*	*1,607*	Costs are evaluated as 1% of CAPEX per year for the full technical lifetime
		Power	MDKK	*1,020*	*1,530*	Based on 0.5 DKK/KWh pricing
		Total acc. OPEX	**MDKK**	**2,627**	**3,137**	
Total cost/t			**DKK/t**	**221**	**166**	
***hereof storage**			**DKK/t**	**114**	**97**	
**hereof transport*			**DKK/t**	**107**	**68**	

Other case-specific assumptions:

- A 400 km CO2 offshore transport pipeline from Hamburg to the North Sea storage sites is included in this set-up carrying 2 MtCO2/y in the 5 MtCO2/y scenario and 3 MtCO2/y in the 10 MtCO2/y scenario
- A 450 km CO2 offshore transport pipeline from Rotterdam to the North Sea storage sites is included in this set-up carrying 2 MtCO2/y in the 5 MtCO2/y scenario and 3 MtCO2/y in the 10 MtCO2/y scenario
- The remaining increase in import volume between the 5 and 10 MtCO2/y cases is assumed to be transported using shuttle tankers to Esbjerg harbour and transported via pipeline to the North Sea storage site
- German CO2 exports not included in the pipeline is assumed to come from Rostock (East of Jutland)
- No CO2 export other than export via pipeline is expected from the Netherlands
- Appraisal wells are not included as the geological structures of the offshore storage sites are assumed to be well known due to prior mapping by the oil and gas industry
- Infrastructure for providing energy offshore is assumed to already be installed and has not been included in the above estimates

- Injection wells are placed in the Northern part of the North Sea oil and gas fields as the geological structure of these sites means fewer wells are needed for the same injection rate compared to the remaining Danish oil and gas fields

7.4 OVERVIEW OF ESTIMATED CCS SHARE BY COUNTRY

Table 60: Estimated CCS share; Finland

Industry	Sub-industry	CO2 Emissions (2017) [Mt]	Technically capturable share	Estimated CCS share (what is actually expected for CCS given alternatives etc)	Comments on estimated CCS share (if relevant)
Power and heat generation	**Thermal power and heat generation**	16,9	90%	N/A	Thermal power and heat generation are not considered relevant, since Finland will employ electrification and other initatives to make up for emissions.
	WtE plants	0,2	90%	90%	Finland has one large WtE facility that is considered relevant if Finland chooses to deploy BECCS, which the country has indicated in its Government strategies that it might.
Industrial plants	**Steel & iron production/ferrous metals**	1,5	60%	60%	Finland has two large iron and steel facilities, which have potential for carbon capture.
	Non-ferrous metals (aluminium, copper and zinc etc)	-	N/A	N/A	N/A
	Mineral oil and gas refineries	3,1	50%	50%	CO2 prduction from refineries using fossil fuels have a potential to utilise CCS.
	Chemicals production	0,7	50%	50%	One petrochemical plant in operation, however, reduction of CO2 emission can also be achieved by easier mesasures (widely available in Finland), i.e., recycling of chemicals and electrification.
	Chemicals production (fertiliser/ammonia production)	-	50%	N/A	N/A
	Pulp & paper	20,3	80%	80%	If Finland chooses to implement BECCS into their climate strategy, the pulp & paper industry is highly suitable; Large volumes of CO2 from biomass in pulp & paper production facilities could be counted as negative emissions if captured and stored, the large factories are often located near rivers,
	Mineral production (cement)	1,3	90%	90%	Two cement plants in operations; use of biofuels can reduce some emissions, however CCS would be highly relvant to achieve carbon neutrality.
	Mineral production (lime and plaster, ceramics, glass and mineral fibers etc)	-	90%	N/A	N/A
	Food processing	-	90%	N/A	N/A
Other	**Other**	2,9	N/A	N/A	N/A
Total		**46,8**			

Table 61: Estimated CCS share; Sweden

Industry	Sub-industry	CO2 Emissions (2017) [Mt]	Technically capturable share	Estimated CCS share (what is actually expected for CCS given alternatives etc)	Comments on estimated CCS share (if relevant)
Power and heat generation	**Thermal power and heat generation**	11,7	90%	N/A	The majority of fossil plants are expected to be phased out by 2050, making any CCS retrofit a less attractive option compared to alternatives such as electrification.
	WtE plants	4,8	90%	90%	WtE plants in Sweden is considered relevant as Sweden has openly cpmmunicated a strategy to deploy BECCS.
Industrial plants	**Steel & iron production/ferrous metals**	4,1	60%	0%	Fossil free production using green hydrogen expected by 2035.
	Non-ferrous metals (aluminium, copper and zinc etc)	0,7	N/A	N/A	N/A
	Mineral oil and gas refineries	2,7	50%	50%	To minimise CO2 emissions, Sweden is expected to retrofit any refinery with carbon capture technologies if the economic return is positive.
	Chemicals production	1,0	50%	25%	The chemical industry is expected to rely roughly 50% on CCS, and 50% on CCU.
	Chemicals production (fertiliser/ammonia production)	-	50%	N/A	
	Pulp & paper	22,8	80%	80%	Large volumes of CO2 from biomass could be captured in the pulp & paper production facilities and counted as negative emissions if stored, the large factories are often located near rivers, making transport of CO2 away from the facilities cheaper and more convenient.
	Mineral production (cement)	2,8	90%	90%	To minimise CO2 emissions, Sweden is expected to retrofit most cement plants with carbon capture technologies if it economically viable.
	Mineral production (lime and plaster, ceramics, glass and mineral fibers etc)	-	90%	N/A	N/A
	Food processing	-	90%	N/A	N/A
Other	**Other**	0,7	N/A	N/A	N/A
Total		**51,3**			

Table 62: Estimated CCS share; Norway

Industry	Sub-industry	CO2 Emissions (2017) [Mt] (From EU-ETS)	Technically capturable share	Estimated CCS share (what is actually expected for CCS given alternatives etc)	Comments on estimated CCS share (if relevant)
Power and heat generation	**Thermal power and heat generation**	14,2	90%	50%	Presumably mainly related to oil & gas activities, energy majors are expected to prioritise CCS due to governmental focus on decarbonisation.
	WtE plants	-	90%	N/A	N/A
Industrial plants	**Steel & iron production/ferrous metals**	2,5	60%	50%	Fossil-reliant industries, such as steel, could choose to use CCS rather than invest in options like hydrogen.
	Non-ferrous metals (aluminium, copper and zinc etc)	2,7	N/A	N/A	N/A
	Mineral oil and gas refineries	2,6	50%	75%	Energy majors see CCS as a way of protecting a chunk of their existing extraction and refining business, because if the technology is proven to work at scale it can potentially offset the CO2 emissions from their operations.
	Chemicals production	1,5	50%	25%	The chemical industry is expected to rely roughly 50% on CCS and 50% on CCU.
	Chemicals production (fertiliser/ammonia production)	-	50%	N/A	N/A
	Pulp & paper	0,2	80%	50%	The pulp & paper industry in Norway is estimated to implement some CCS to achieve negative emissions.
	Mineral production (cement)	1,2	90%	90%	To minimise CO2 emissions, Norway is expected to retrofit most cement plants with carbon capture technologies if it is technologically possible.
	Mineral production (lime and plaster, ceramics, glass and mineral fibers etc)	0,5	90%	90%	Due to the large support towards CCS from the government, carbon capture technologies are expected to be widely installed in any industry where economically viable.
	Food processing	-	90%	N/A	N/A
Other	**Other**	-	N/A	N/A	N/A
Total		**25,4**			

Table 63: Estimated CCS share; UK

Industry	Sub-industry	CO2 Emissions (2017) [Mt]	Technically capturable share	Estimated CCS share (what is actually expected for CCS given alternatives etc)	Comments on estimated CCS share (if relevant)
Power and heat generation	**Thermal power and heat generation**	99,7	90%	10%	The UK plans to develop a hydrogen economy to supply industrial processes, long-distance HGVs and ships, and for electricity and heating. For heating, by 2035, existing homes should replace their heating systems for it to be low-carbon or ready for hydrogen, so that the share of low-carbon heating increases from 4.5% today to 90% in 2050. The hydrogen used in the CCC scenarios are assumed to come mainly from steam methane reforming with CCS in the UK.
	WtE plants	9,9	90%	80%	Expected to be prioritised highly and that any WtE plant built, after 2040, will have the technology deployed from the beginning.
Industrial plants	**Steel & iron production/ferrous metals**	6,7	60%	50%	Carbon capture is the only current technology that abates carbon emissions at scale for the steel & iron industry, and CCS is expected to be highly prioritised compared to CCU within the industry.
	Non-ferrous metals (aluminium, copper and zinc etc)	-	N/A	N/A	N/A
	Mineral oil and gas refineries	10,8	50%	25%	CCS faces competiton in this industry from electrification, and hydrogen and thus, a 50% allocation towards CCS is expected.
	Chemicals production	4,8	50%	25%	CCS faces competiton in this industry from electrification, hydrogen and CCU, a 50% allocation towards CCS is expected.
	Chemicals production (fertiliser/ammonia production)	0,6	50%	25%	
	Pulp & paper	-	80%	N/A	N/A
	Mineral production (cement)	7,2	90%	90%	Carbon capture is the only current technology that can abate carbon emissions at scale for the cement industry, and thus, CCS is expected to be highly prioritised.
	Mineral production (lime and plaster, ceramics, glass and mineral fibers etc)	1,0	90%	90%	Carbon capture is the only current technology that abates carbon emissions at scale for the mineral industry, and CCS is expected to be highly prioritised compared to CCU and other abatement technolgies within the industry.
	Food processing	1,2	90%	50%	Carbon capture is the only current technology that abates carbon emissions at scale for the food processing industry, however CCS is expected to be prioritised equally with other developing abatement technolgies like
Other	**Other**	4,4	N/A	N/A	N/A
Total		**146,3**			

Table 64: Estimated CCS share; Germany

Industry	Sub-industry	CO2 Emissions (2017) [Mt]	Technically capturable share	Estimated CCS share (what is actually expected for CCS given alternatives etc)	Comments on estimated CCS share (if relevant)
Power and heat generation	**Thermal power and heat generation**	263,8	90%	5%	Germany has a cliamte neutrality target in 2050 and aims to reduce emissions by 95% and the last 5% will need to be removed with technology such as CCS.
	WtE plants	16,4	90%	50%	BECCS is listed by the goverment as one of the CCS focus areas, and WtE is possibly the largest BECCS applications.
Industrial plants	**Steel & iron production/ferrous metals**	28,6	60%	20%	Green hydrogen is prioritised, however, Germany cannot produce all the green hydrogen they need by itself, and is, therfore, expected to collaborate with other countries. However, blue hydrogen is expected to be a transitional solution.
	Non-ferrous metals (aluminium, copper and zinc etc)	1,7	N/A	N/A	N/A
	Mineral oil and gas refineries	21,1	50%	30%	High priority due to the long-term commitment made to natural gas via the Nord Stream pipeline.
	Chemicals production	24,6	50%	30%	CCS is not expected to be prioritised as highly as in other industries due to a focus on CCU.
	Chemicals production (fertiliser/ammonia production)	-	50%	0%	Expected to be replaced entirely with zero-carbon technologies.
	Pulp & paper	-	80%	N/A	N/A
	Mineral production (cement)	25,0	90%	50%	Most new cement plants are expected to implement carbon capture technologies for the purpose of storage, however as there are currently a lot of cement factories in DE which are either old or small, only around 50% of the total emissions from the cement industry is expected to be captured and stored.
	Mineral production (lime and plaster, ceramics, glass and mineral fibers etc)	0,9	90%	N/A	N/A
	Food processing	0,8	90%	N/A	N/A
Other	**Other**	23,3	N/A	N/A	N/A
Total		**406,2**			

Table 65: Estimated CCS share; The Netherlands

Industry	Sub-industry	CO2 Emissions (2017) [Mt]	Technically capturable share	Estimated CCS share (what is actually expected for CCS given alternatives etc)	Comments on estimated CCS share (if relevant)
Power and heat generation	**Thermal power and heat generation**	55,7	90%	5%	Small part of the energy mix is renewable, which is expected, due to the high population density and thus low room for renewable energy generation technology. NL had problems reaching their 2020 goals and is expected to continue using gas fired power plants for some time.
	WtE plants	8,9	90%	90%	WtE plants are expected to be used long-term and thus, makes for an obvious choice to retrofit carbon capture equipment and reach negative emissions by storing it afterwards.
Industrial plants	**Steel & iron production/ferrous metals**	-	60%	N/A	N/A
	Non-ferrous metals (aluminium, copper and zinc etc)	-	N/A	N/A	N/A
	Mineral oil and gas refineries	10,6	50%	90%	CCS will be prioritised highly as it is the only current technology that can abate emissions at the expected scale of the mineral oil and gas refinery industry in the Netherlands.
	Chemicals production	16,9	50%	75%	In general, in the chemical industry in the NL CCS is expected to be prioritised over CCU or other emission abatement technologies
	Chemicals production (fertiliser/ammonia production)	-	50%	75%	
	Pulp & paper	-	80%	N/A	N/A
	Mineral production (cement)	0,5	90%	90%	High priority as current emissions from the cement production process are hard to abate with any other current technology.
	Mineral production (lime and plaster, ceramics, glass and mineral fibers etc)	0,1	90%	N/A	N/A
	Food processing	0,9	90%	N/A	N/A
Other	**Other**	1,4	N/A	N/A	N/A
Total		**95,0**			

Table 66: Estimated CCS share; Poland

Industry	Sub-industry	CO2 Emissions (2017) [Mt]	Technically capturable share	Estimated CCS share (what is actually expected for CCS given alternatives etc)	Comments on estimated CCS share (if relevant)
Power and heat generation	**Thermal power and heat generation**	121,2	90%	30%	Decarbonisation of the Polish power & heat generation sector will be driven by electrification, but some newer coal plants, upcoming natural gas plants and CPH plants will be relevant for CCS. There are currently 4 coal plants, 7 MSW/CPH plants and 2 natural gas plants that are newer and relevant: Total emissions at 28Mt/y. Furthermore, 5 natural gas plants are planned (all planned at around 2025) with total emissions at 6Mt/y. Therefore, total emissions at these plants are ~30Mt/y, of which 10Mt/y (30%) estimated to have CCS potential.
	WtE plants	-	90%	N/A	N/A
Industrial plants	**Steel & iron production/ferrous metals**	7,1	60%	30%	Due to fossil industry dominance, blue hydrogen is expected to play key role as a transitional technology, therfore a high CCS potential is expected.
	Non-ferrous metals (aluminium, copper and zinc etc)	1,2	N/A	N/A	N/A
	Mineral oil and gas refineries	1,7	50%	50%	CCS is a last resort technology at scale in Poland, however, there is a potential for blue hydrogen to become a transitional fuel in Poland, making CCS necessary.
	Chemicals production	1,0	50%	10%	CCU expected to be prioritised over CCS in Poland.
	Chemicals production (fertiliser/ammonia production)	1,7	50%	10%	
	Pulp & paper	-	80%	N/A	N/A
	Mineral production (cement)	6,8	90%	50%	CCS considered a relevant option. Some of the industry is looking intro RDF (Refused-derived fuel) instead of fossil fuels, however, also here BECCS could be relevant to obtain negative emissions and compensate for other industries that are hard to abate.
	Mineral production (lime and plaster, ceramics, glass and mineral fibers etc)	2,1	90%	40%	CCS is a last resort technology for emissions abatement at scale in Poland, so other technologies like CCU and electrification will be explored first.
	Food processing	-	90%	N/A	N/A
Other	**Other**	23,8	N/A	N/A	N/A
Total		**166,7**			

Table 67: Estimated CCS share; Estonia

Industry	Sub-industry	CO2 Emissions (2017) [Mt]	Technically capturable share	Estimated CCS share (what is actually expected for CCS given alternatives etc)	Comments on estimated CCS share (if relevant)
Power and heat generation	**Thermal power and heat generation**	7,9 (20,7)	90%	5%	The number (20.7 Mt in 2017) is outdated since a number of fossil fuel driven plants were close in the past couple of years. Therefore a more represenative number is 7.9 Mt than as provided by the E-PRTR in 2017. Since Estonia closed down oil-shale driven plants quite rapidly in the past couple of years, the country's energy supply security has been at risk. For this reason, the existent oil-shale plants will need to keep running until at least 2035 to secure the country's energy supply, which is why 5% is assumed to be potential for CCS in these fossil fuel driven plants. The oil-shale plants will be phased-out after 2035 according to strategy plans.
	WtE plants	-	90%	N/A	N/A
Industrial plants	**Steel & iron production/ferrous metals**	-	60%	N/A	N/A
	Non-ferrous metals (aluminium, copper and zinc etc)	-	N/A	N/A	N/A
	Mineral oil and gas refineries	-	50%	N/A	N/A
	Chemicals production	-	50%	N/A	N/A
	Chemicals production (fertiliser/ammonia production)	-	50%	N/A	N/A
	Pulp & paper	-	80%	N/A	N/A
	Mineral production (cement)	0,6	90%	90%	High priority as current emissions from the cement production process are hard to abate with any other current technology.
	Mineral production (lime and plaster, ceramics, glass and mineral fibers etc)	-	90%	N/A	N/A
	Food processing	-	90%	N/A	N/A
Other	**Other**	3,4	N/A	N/A	N/A
Total		**11,9**			

Table 68: Estimated CCS share; Lithuania

Industry	Sub-industry	CO2 Emissions (2017) [Mt]	Technically capturable share	Estimated CCS share (what is actually expected for CCS given alternatives etc)	Comments on estimated CCS share (if relevant)
Power and heat generation	**Thermal power and heat generation**	-	90%	N/A	N/A
	WtE plants	0,1	90%	20%	WtE plants considered relevant for CCS in general, however, Lithuania has not communicated any strategy to deploy BECCS in this sector.
Industrial plants	**Steel & iron production/ferrous metals**	-	60%	N/A	N/A
	Non-ferrous metals (aluminium, copper and zinc etc)	-	N/A	N/A	N/A
	Mineral oil and gas refineries	1,7	50%	0%	Expected to be replaced entirely with green hydrogen
	Chemicals production	-	50%	N/A	N/A
	Chemicals production (fertiliser/ammonia production)	2,6	50%	30%	CCU is preferred over CCS; however it is still unproven at scale compared with CCS. CCS expected to me a medium-term solution at best.
	Pulp & paper	-	80%	N/A	N/A
	Mineral production (cement)	0,7	90%	90%	CCS is expected to take the majority share in the cement industry in Lithuania as it is expected to be the cheapest abatement option.
	Mineral production (lime and plaster, ceramics, glass and mineral fibers etc)	-	90%	N/A	N/A
	Food processing	-	90%	N/A	N/A
Other	**Other**	-	N/A	N/A	N/A
Total		**5,2**			

Table 69: Estimated CCS share; Latvia

Industry	Sub-industry	CO2 Emissions (2017) [Mt]	Technically capturable share	Estimated CCS share (what is actually expected for CCS given alternatives etc)	Comments on estimated CCS share (if relevant)
Power and heat generation	**Thermal power and heat generation**	1,0	90%	20%	Low potential as the Latvian Government will phase out emissions in this sector and has promoted the potential for CCS in industrial activities and not power and heat. However, no industiral installations currently produce more than 100 ktCO2/y.
	WtE plants	-	90%	N/A	N/A
Industrial plants	**Steel & iron production/ferrous metals**	-	60%	N/A	N/A
	Non-ferrous metals (aluminium, copper and zinc etc)	-	N/A	N/A	N/A
	Mineral oil and gas refineries	-	50%	N/A	N/A
	Chemicals production	-	50%	N/A	N/A
	Chemicals production (fertiliser/ammonia production)	-	50%	N/A	N/A
	Pulp & paper	-	80%	N/A	N/A
	Mineral production (cement)	-	90%	N/A	N/A
	Mineral production (lime and plaster, ceramics, glass and mineral fibers etc)	-	90%	N/A	N/A
	Food processing	-	90%	N/A	N/A
Other	**Other**	-	N/A	N/A	N/A
Total		**1,0**			

OKTOBER 2021
KEFM

CCS - INTERNATIONALE ERFARINGER - SIKKERHED, NATUR OG MILJØ

COWI

ADRESSE COWI A/S
Parallelvej 2
2800 Kongens Lyngby

TLF +45 56 40 00 00
FAX +45 56 40 99 99
WWW cowi.dk

OKTOBER 2021
KEFM

CCS - INTERNATIONALE ERFARINGER - SIKKERHED, NATUR OG MILJØ

PROJEKTNR.	DOKUMENTNR.
A231499	A231499-01

VERSION	UDGIVELSESDATO	BESKRIVELSE	UDARBEJDET	KONTROLLERET	GODKENDT
04	15 oktober 2021		NMSC, LOVGX, LOKL, EMJT, PEFI, MMK	LNKR/CCRN	MMK

INDHOLD

1	Baggrund og formål	7
2	Metode, afgrænsning og struktur	9
2.1	Metode og afgrænsning	9
2.2	Struktur	11
3	Opsummering og perspektivering	12
3.1	Summary	12
3.2	CO_2-fangstanlæg – sikkerhed, miljø og natur	15
3.3	CO_2-mellemlager - sikkerhed, miljø og natur	17
3.4	CO_2 geologisk lagring – sikkerhed, natur og miljø	18
3.5	CO_2-transport infrastruktur	21
4	Oversigt over relevante internationale projekter	24
5	Sikkerheds- og miljømæssige forhold	30
5.1	Kuldioxid (CO_2)	30
5.2	Aminer	34
5.3	Ammoniak (NH_3)	34
5.4	Oxygen (O_2)	35
6	CO_2-fangstanlæg - Vurdering af sikkerhed, natur og miljø	37
6.1	Sikkerhed	37
6.2	Miljø	38
6.3	Natur	43
7	Mellemlager faciliteter - Vurdering af sikkerhed, natur og miljø	44
7.1	Sikkerhed	44

7.2 Miljø 45
7.3 Natur 46

8 Geologisk lagring af CO_2 på land og til havs - Vurdering af sikkerhed, natur og miljø 48
8.1 Sikkerhed 48
8.2 Miljø 49
8.3 Natur 53

9 Transport af CO_2 på land og til havs - Vurdering af sikkerhed, natur og miljø 63
9.1 Sikkerhed 63
9.2 Miljø 64
9.3 Natur 66

10 Referencer 68

BILAG

Bilag A Teknisk beskrivelse af CCS anlæg
A.1 CO_2-fangstanlæg
A.2 Mellemlager-faciliteter
A.3 Geologisk lagring af CO_2 på land og til havs.
A.4 Transport af CO_2 på land og til havs

Bilag B Opsummering af CCS erfaringer med sikkerhed, miljø og natur

Bilag C Longlist over litteratur gennemgået

1 Baggrund og formål

I klimaaftalen for energi og industri mf. (juni 2020) aftalte et bredt flertal af Folketingets partier, at der fremover skal være mulighed for fangst, transport og lagring af CO_2 i Danmark og for at transportere indfanget CO_2 på tværs af landegrænser under forudsætning af, at det foregår under forsvarlige sikkerheds- og miljømæssige forhold.

Dette er i juni 2021 fulgt op af en bred aftale mellem regeringen og en lang række partier i Folketinget om en køreplan for lagring af CO_2. En aftale, hvori det af parterne anerkendes, at Carbon Capture and Storage (CCS) er et centralt virkemiddel for at afbøde klimaforandringerne internationalt og som bakker op om, at CCS skal spille en væsentlig rolle i bestræbelserne for at nå de nationale klimamål. Aftalen understreger, at der skal skabes et grundlag for sikker og miljømæssig forsvarlig lagring af CO_2 i undergrunden, og at der skal sættes gang i yderligere undersøgelse af lagringsfaciliteter i Danmark [1].

Formålet med denne rapport er at beskrive internationale erfaringer med CCS med hensyn til sikkerheds-, natur- og miljømæssige forhold, således at dette kan indgå i det videre arbejde med sikring af disse forhold i forbindelse med dansk anvendelse af CCS som klimavirkemiddel. Rapporten skal dermed også forholde sig til, hvorvidt de internationale erfaringer er relevante i en dansk sammenhæng.

Rapporten skal indgå som baggrund og afgrænsning af det videre arbejde med udvikling af CCS i Danmark, hvilket vil omfatte strategisk miljøvurdering af udbud af arealer for injektion og geologisk lagring af CO_2 i undergrunden samt miljøvurdering og miljøgodkendelse af helt konkrete projekter for CCS.

CCS omfatter fangstanlæg på CO_2 punktkilder, infrastruktur til transport, mellemlagerfaciliteter samt permanent geologisk lagring i undergrunden.

CO_2-fangst er velkendt teknologi som siden først i 1970'erne har været anvendt i olieindustrien specielt USA til at forbedre indvindingspotentiale i olielagre (enhanced oil recovery (EOR)).

Siden 1996 har CO_2-fangst og lagring været anvendt i Norge til at reducere CO_2-udledninger fra indvinding af gas i Nordsøen. Den opfangede CO_2 sendes til permanent lagring i strukturer tæt på gasindvindingsområderne i Sleipner og Snøhvitfelterne.

CO_2-fangst anvendes i Danmark i forbindelse med opgradering af biogas og har på forsøgsbasis være afprøvet på Esbjergværket. En mindre del af den opsamlede CO_2 anvendes i medicinal- og fødevareindustri.

Transport af CO_2 mellem opsamlings- og anvendelsessted sker for nuværende i Danmark primært med tankvogne. Der er endnu ikke foretaget geologisk lagring af CO_2 i Danmark.

På globalt plan opererer der i dag 27 kommercielle CCS-faciliteter med en samlet kapacitet til at fange og lagre ca. 40 mio. tons CO_2 per år [2]. De er primært baseret i USA altovervejende som en del af øget olieindvinding (EOR).

Herudover eksisterer en række pilot- og demonstrationsprojekter verden over, med fokus på at udvikle og teste teknologi samt projekter i mere eller mindre moden udvikling. Blandt andet er man i Norge påbegyndt et feasibility- og konceptstudie for Longship projektet. Det er en realisering af et fuldskala CCS projekt med CO_2-fangst, skibstransport, mellemlagring og transport til offshore lager via rør.

2 Metode, afgrænsning og struktur

2.1 Metode og afgrænsning

Udgangspunktet for rapporten har været tilgængelig litteratur, forskningsrapporter, konsulentrapporter samt information fra diverse organisationer (f.eks.: Global CCS Institute, IEA, UK EPA) vedr. internationale CCS-projekter inkl. eventuelle pilot- og testprojekter.

En komplet litteraturliste fremgår af bilag C.

For at indkredse relevante anlæg og projekter er der indledningsvis lavet en oversigt over internationale CCS-anlæg inkl. pilot og testanlæg samt projekter på bedding, hvorfra erfaringer kunne være relevante.

Rapporten beskriver, i det omfang de foreligger, internationale erfaringer for alle de enkelte led i CCS-kæden, det vil sige: 1) CO_2-fangst, 2) mellemlagring og 3) lagring samt 4) infrastruktur til transport.

For hver af de forskellige led i kæden (1-4) er redegjort for erfaringer med hensyn til sikkerhed, miljø og natur ved forundersøgelser, anlæg og etablering, drift og afvikling.

Der hvor det ikke har været muligt at identificere eksplicitte internationale erfaringer er det anført.

2.1.1 Relevans for danske forhold

Der er i erfaringsopsamlingen fokuseret på de anlægstyper/metoder, som vurderes at være relevante i dansk sammenhæng, det vil sige, der er ikke medtaget erfaringer fra brug af CO_2 til et øge olieudvinding (EOR), og der er fokuseret på CO_2 fangstmetoder, som dels er teknisk modne, kommercielle samt relevante for større danske punktkilder og biogasanlæg.

Yderligere er der i forbindelse med opsummering og perspektivering af de internationale erfaringer med sikkerhed, miljø og natur vurderet og taget stilling til relevans i en dansk kontekst. Det kan f.eks. være, hvorvidt de beskrevne miljøpåvirkninger er sammenlignelige eller hvorvidt påvirkede naturtyper og habitater er relevante og sammenlignelige.

2.1.2 Tekniske anlæg

CO_2-fangst vil kunne være relevant for større punktkilder, hvor der ønskes en reduktion af den direkte udledning af CO_2. Det kan være fra eksempelvis cementproduktion, kraftvarmeanlæg (inklusiv de affalds- og biomasssefyrede anlæg) samt biogasanlæg.

CO_2-fangstteknologier afgrænses specifikt til anlæg med højteknologisk modenhed, som allerede er eller er tæt på at være kommercielt tilgængelige, det vil sige:

- Rensning af røggas (post combustion) ved hhv. aminvask og nedkølet ammoniak (oftest benævnt chilled ammonia)

- Dannelse af røggas med høj CO_2-koncentration ved forbrænding ved iltrige betingelser (oxyfuel).

Mellemlagerfaciliteter vil omfatte lagring i tanke samt med stor sandsynlighed kondensering / liquefaction-faciliteter.

Lagring af CO_2 finder sted i geologiske strukturer med stort porevolumen (f.eks. i sandsten) overlejret af et impermeabelt lag (f.eks. lersten). Lagring vil under danske forhold typisk skulle ske 1-2 km. under overfladen. Potentielt egnede strukturer til lagring i Danmark findes både offshore, tæt på land og på land. Der overvejes både CO_2-lagring i tidligere oliegasfelter og i nye uafprøvede strukturer.

I Bilag A fremgår en mere detaljeret beskrivelse af de forskellige tekniske anlæg. De er så vidt muligt beskrevet medhensyn til forundersøgelser, anlæg og etablering, drift og afvikling.

2.1.3 Sikkerhed

Sikkerhed omfatter de aspekter ved CCS, som knytter sig til pludselige hændelser, som specifikt har med håndteringen af CO_2 og tilknyttede hjælpestoffer at gøre, og som kan udgøre en fare for menneskers liv og helbred. Hændelserne medfører enten udsættelse for farlige stoffer, fysiske påvirkninger eller for begge dele. Påvirkning af natur og miljø ved pludselige hændelser behandles under henholdsvis natur- og miljøafsnittene.

Generelle arbejdsmiljømæssige farer fra aktiviteter som konstruktionsarbejde på store industriprojekter, herunder offshore installationer, transport af gods på landevej, jernbane og skib og transport af stoffer i rørledninger, er ikke behandlet, medmindre, der er forhold, som er specifikke for CCS.

2.1.4 Miljø

Under miljø indgår udledninger til luft, vand og jord. Herudover indgår energiforbrug og CO_2 aftryk, brug af ressourcer samt affald.

2.1.5 Natur

Under natur indgår vurdering af inddragelse af arealer samt påvirkninger af arter, habitater og økosystemer som følge fysisk aktivitet, støj, emissioner til luft, vand og jord og uheld med udledning af farlige stoffer. Der inkluderes både de midlertidige og de mere langsigtede påvirkninger.

2.2 Struktur

For at indkredse de internationale anlæg og projekter, hvorfra det vil være relevant at indhente erfaringer er der i afsnit 3 lavet en oversigt over internationale CCS-anlæg inkl. pilot og testanlæg samt projekter på bedding.

Med udgangspunkt i dels de projekter der findes internationalt samt de tekniske anlæg og de forskellige faser (forundersøgelser, anlæg etablering, drift og afvikling) beskrives ud fra relevante referencer og erfaringer de væsentligste sikkerheds-, miljø- og naturmæssige forhold.

De sikkerhedsmæssige forhold er for alle de enkelte led i CCS-kæden relateret til større udslip af farlige stoffer, f.eks. CO_2. For at undgå gentagelser er der i afsnit 5 udarbejdet en generel beskrivelse af de relevante stoffer samt de sikkerheds- og miljømæssige forhold i forbindelse med større udslip.

Rapporten er opbygget således, at der startes med erfaringer for CO_2 fangst, CO_2 mellemlager, CO_2 lagring og til sidst medtager CO_2 infrastruktur.

I Bilag A fremgår en beskrivelse af de tekniske anlæg fordelt på faserne forundersøgelser, anlæg og etablering, drift og afvikling.

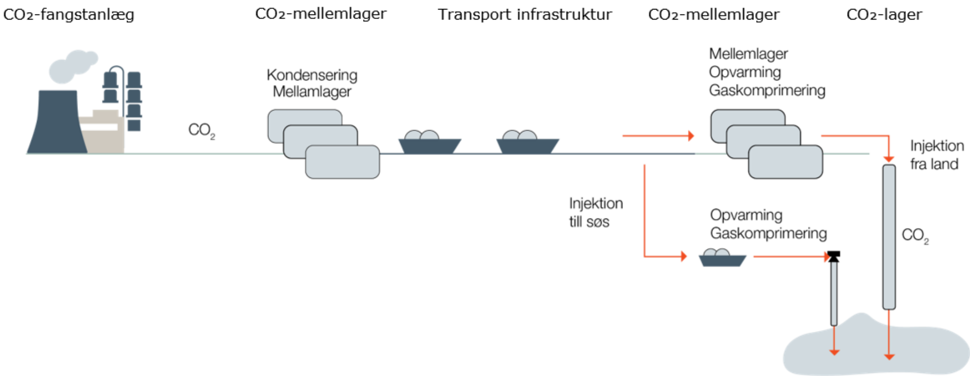
I Bilag B er lavet en opsummering af de væsentligste sikkerheds-, natur- og miljømæssige forhold identificeret i undersøgelsen.

I Bilag C fremgår en "longlist" over den samlede litteratur, der er gennemgået i forbindelse med udarbejdelse af rapporten.

3 Opsummering og perspektivering

Nedenfor præsenterer vi opsummeringen af de væsentligste erfaringer vedrørende sikkerhed, miljø og natur for CCS[1]. Erfaringerne er identificeret ved en gennemgang af relevante internationale projekter og erfaringer. Erfaringerne er opsummeret dels meget overordnet i afsnit 3.1, dels lidt mere i detalje for hvert enkelt led i CCS-kæden i afsnit 3.2-3.5. Endvidere henvises til bilag B for en samlet oversigtlig opsummering af sikkerheds-, miljø- og naturmæssige forhold ved CCS.

Figur 1 giver et overblik over de enkelte led i CCS værdikæden. Den endelige konfiguration kan se ud på mange måder og vil afhænge af det konkrete projekt.



Figur 1: Illustration af de enkelte led i en CCS værdikæde

3.1 Summary

Helt generelt og på tværs af de enkelte led og projekter er erfaringerne med hensyn til CCS og sikkerheds-, miljø- og naturmæssige forhold:

- Der er international erfaring med CCS omfattende både offshore og onshore geologisk lagring af CO_2
- Langt de fleste kommercielle CCS projekter er etableret med henblik på Enhanced Oil Recovery
- CO_2-fangst er en moden teknologi, og der er leverandører på markedet, der kan levere anlæg, som efterlever krav til sikkerhed, miljø og natur
- Der anvendes meget energi til CO_2-fangst, konditionering og transport, og det er vigtigt at have fokus på energieffektivitet og optimering i hele kæden

[1] CCS: Carbon Capture and Storage

- Internationale projekter for CO_2 lagring har tilknyttet et omfattende monitoreringsprogram både i forbindelse med forundersøgelse, drift og afvikling af lageret

- Overvågning udført i forbindelse med de internationale lagre har vist, at CO_2 forbliver sikkert i lageret, og der er ikke konstateret CO_2-udslip fra nogen af de eksisterende geologiske lagre.

Desuden viser erfaringerne at anlæg, etablering samt afvikling af CO_2-fangstanlæg og mellemlagerfaciliteter sker som for andre typiske industri-/procesanlæg og at de ikke medfører væsentlige specifikke sikkerheds-, miljø- og naturmæssige påvirkninger. Påvirkningerne er primært relateret til et arealbehov og eventuel inddragelse af beskyttede eller sårbare naturtyper samt til forstyrrelser, som følge af fysiske indgreb, trafik og støj. Påvirkningerne af miljø og natur vil afhænge af den konkrete placering i forhold til beskyttede områder og nærhed til nærmeste naboer.

Under drift af CO_2-fangstanlæg er den væsentligste bekymring identificeret i de internationale referencer, de aminbaserede anlægs udledninger til luft. En målrettet indsats har ført til en udvikling af fangstanlæggene, de aminer der anvendes samt metoderne til at vurdere den miljømæssige påvirkning. I Norge er man langt fremme med etablering af større fangstanlæg på landbaserede kilder, som er godkendt af de norske myndigheder.

I drift af anlæggene skal der ved større oplag af CO_2 endvidere tages hensyn til de risikomæssige forhold ved placering af anlæggene.

I forhold til sikkerhed og geologisk lagring af CO_2 er erfaringerne positive. Der er ikke fundet eksempler på uheld og større udslip af CO_2 fra geologiske CO_2 lagre, ej heller store udsivninger på grund af migrering af den oplagrede CO_2.

Det vurderes, at godt kendskab til lageret og dets egenskaber, løbende monitorering samt placering i områder med lav tektonisk aktivitet betyder, at der er lav risiko for større udslip af CO_2.

Seismiske undersøgelser er en vigtig aktivitet i monitorering af lagrene og der er i de internationale referencer fokus på denne aktivitet og de afledte påvirkninger på fisk og marine pattedyr. Det er vurderet, at den skadelige påvirkning af fisk og pattedyr som følge af seismiske undersøgelser og overvågning typisk medfører en lokal, midlertidig påvirkning, som kan reduceres med passende afværgeforanstaltninger.

Påvirkningen skal dog ses i sammenhæng med øvrige aktiviteter og marine påvirkninger i samme influensområde. Afværgeforanstaltninger som medfører, at marine pattedyr skræmmes væk fra et område, forudsætter eksempelvis, at der er upåvirkede områder i nærheden.

Ved seismiske undersøgelser på land anvendes store og tunge køretøjer, der kan sætte aftryk i landskabet, beskadige vegetation og det øverste jordlag. Der kan også være tale om forstyrrelser af fugle- og dyrevildt samt øvrige beskyttede arter. Påvirkningerne kan reduceres med afværgeforanstaltninger, som eksempelvis tidsmæssig planlægning af arbejdet for at undgå sårbare perioder, udlæg af køreplader m.m.

I forbindelse med forundersøgelser og anlæg af de geologiske lagre beskrives endvidere påvirkninger som fysiske forstyrrelser af havbund, udledninger til vand af kemikalier, boremudder, borespåner og cement samt støj, emissioner og energiforbrug fra skibe og borerig. Det er påvirkninger som er sammenlignelige med dem som identificeres og håndteres i forbindelse med olie- og gasudvinding i Nordsøen.

Påvirkningerne i forbindelse med anlæg og etablering af geologisk lager på land vurderes at være mindre end for offshore lagre. Specielt seismiske undersøgelser vil ikke have samme påvirkning på land, da lyd propagerer hurtigere og længere i vand end i atmosfærisk luft [3]. På land vil der endvidere i langt større omfang være mulighed for at opsamle affald og udledninger.

Påvirkninger fra drift af et geologisk lager inkluderer diffus udledning af CO_2 fra ventilering, tryksatte koblinger mv, støj fra udstyr, udledning af kemikalier samt energiforbrug og emissioner.

Væsentligheden af de miljø- og naturmæssige påvirkninger både offshore og på land vil afhænge af den konkrete placering herunder nærheden til f.eks. § 3 lokaliteter, truede arter, beskyttede områder samt områder med beboelse.

I forbindelse med transport af CO_2 er påvirkningerne fra skibs-, tog- og lastbilstransport primært støj og emissioner. Ved etablering og placering af rørledninger, vil der være en permanent fysisk ændring og påvirkning langs tracé, både hvis det sker offshore og på land. Herudover vil der være en række mere midlertidige påvirkninger i anlægsfasen som støj, energiforbrug og emissioner samt lys. Etableres rørene til havs kan der endvidere opstå risiko for midlertidig spredning af sediment samt midlertidig forstyrrelse af vandsøjlen.

De natur- og miljømæssige påvirkninger vil afhænge af den konkrete placering af transportkorridoren herunder nærheden til f.eks. § 3 lokaliteter, truede arter ,beskyttede områder og boliger.

Nedenfor gennemgås de væsentligste sikkerheds-, miljø- og natur forhold i hvert af de fire led i værdikæden vist i Figur 1: CO_2-fangst, mellemlager, geologisk lagring og CO_2-transport.

3.2 CO_2-fangstanlæg – sikkerhed, miljø og natur

CO_2 fangstanlæg vil typisk placeres i nærhed af en CO_2 punktkilde og er dermed en del af et større industrielt anlæg. Både rensning af røggas (post combustion) ved hhv. aminvask og nedkølet ammoniak samt oxyfuel processen kan etableres som en del af nye anlæg eller etableres som retrofit på eksisterende punktkilder.

CO_2 fangst er kendt teknologi og de internationale erfaringer med sikkerhed, miljø og natur vil kunne bruges i dansk sammenhæng, da teknologien i hovedtræk vil være ens.

For CO_2-fangstanlæg vil de tekniske forundersøgelser typisk skulle afdække muligheder for udnyttelse af overskudsvarme, afdækning af kølebehov samt integration med damp- og fjernvarmesystemer for at sikre høj energieffektivitet. Ved retrofit kan der være behov for, at der samtidig etableres yderligere rensning af røggas for at få fangstanlægget til at fungere.

Forundersøgelser knyttet til fangstanlæg forventes ikke i sig selv at have væsentlige sikkerheds-, miljø- og naturmæssige forhold. Det forventes, at CO_2 fangstanlæggene også i dansk sammenhæng typisk vil etableres som en del af et større industrianlæg.

Det skal i forbindelse med planlægning sikres, at den valgte placering sker under hensyn til de risiko-, miljø- og naturmæssige forhold, som gælder på den enkelte lokalitet. Det nødvendige plangrundlag skal tilvejebringes, og de nødvendige tilladelser indhentes.

Anlæg og etablering af CO_2-fangstanlæg vil foregå som for andre typiske industri-/procesanlæg. På basis af de internationale erfaringer vurderes anlæggene ved anlæg og etablering ikke at omfatte væsentlige og specifikke sikkerheds-, miljø- og naturmæssige forhold.

Under drift er den væsentligste bekymring, som er identificeret i de internationale referencer, de aminbaserede anlægs udledninger til luft. Med røggassen kan der forekomme emissioner af amin, ammoniak (NH_3), flygtige organiske stoffer (VOC) samt toksiske nitrosaminer og nitraminer fremkommet ved reaktion med NO_X. For chilled ammonia processen er det primært udledning af ammoniak, der nævnes.

Der er erfaringer fra Norge og England, som man med fordel kan drage nytte af i en dansk sammenhæng.

I Norge har man udviklet en metode (toolbox) til at vurdere udledninger til luft, herunder både den direkte emission, koncentrationer af forurenende stoffer i omgivelserne (immissioner) samt deposition. Folkhelseinstituttet har i den forbindelse sat grænseværdier for koncentration af nedbrydningsprodukter i omgivelserne. Den løbende udvikling af CO_2-fangstmetoder og anlæg har betydet, at flere leverandører i dag er i stand til at levere anlæg, som lever op til de norske krav.

I Storbritannien har Environment Agency i 2021 udgivet et BAT Review og en vejledning for CO_2-fangst og i samme anledning defineret grænseværdier for luft for både aminen MEA og nedbrydningsproduktet NDMA.

I dansk sammenhæng er der allerede i forvejen defineret B-værdier for enkelte aminer, som kan bruges i forbindelse med godkendelse af anlæg. Der foreligger dog p.t. ikke B-værdier for nedbrydningsprodukterne Nitrosaminer og Nitraminer og ej heller for alle aminer, som erfaringsmæssigt anvendes til CO_2-fangstanlæg.

Der foreligger i dansk sammenhæng, som grundlag for godkendelser, generelle metoder for beregning af immission og også deposition af udvalgte stoffer. Det skal vurderes, hvorvidt disse er brugbare, eller om der skal udvikles nye metoder inkl. vejledninger. Der kan i den sammenhæng hentes inspiration i Norge, som allerede har godkendt anlæg og i Storbritannien som via BAT-Review for CO_2 fangstanlæg også har sat grænseværdier for udvalgte stoffer.

For fangstanlæg med chilled ammonia skal der tilsvarende være foranstaltninger, der reducerer udledning af ammoniak (NH_3), og som sikrer, at anlægget lever op til gældende grænseværdier. Ammoniak er et kendt stof, som der findes gængse metoder og grænseværdier til at vurdere på basis af.

Der vil være behov for i de konkrete tilfælde at vurdere, om de aminbaserede anlæg og anlæg med ammoniak bliver omfattet af Risikobekendtgørelsen.

Den primære problemstilling i forhold til et fangstanlæg baseret på oxyfuel er tilstedeværelsen af rent ilt, idet ilt er brandnærende. Ved oplag af ilt i mængder over 200 ton vil anlæg være kolonne 2 anlæg og dermed være omfattet af Risikobekendtgørelsen.

I de internationale referencer nævnes energiforbrug og det relaterede CO_2-footprint som faktorer, der potentielt kan udgøre en væsentlig miljøpåvirkning for CO_2 fangstanlægget. Energiforbruget vil afhænge dels af fangstmetoden, men også af integrationen med øvrige processer samt muligheden for at komme af med varme til f.eks. fjernvarme.

Der er ikke via de internationale referencer identificeret væsentlige påvirkninger på natur af CO_2-fangstanlæg. Og der er ikke fundet referencer, der meget specifikt har redegjort for den naturmæssige påvirkning af emissioner og eventuelle depositioner.

I en dansk sammenhæng vil anlæggets deposition af giftige stoffer skulle vurderes i forhold til en konkret placering, nærhed til sårbare naturområder samt eventuelle tålegrænser.

Der er ikke fundet eksempler i de internationale referencer for CO_2-fangstanlæg, der ved uheld har resulteret i et større udslip af CO_2, aminer eller andre forurenende stoffer.

Den stående mængde CO_2 i et fangstanlæg vurderes at være forholdsvis lille, da CO_2 først i forbindelse med mellemlagring komprimeres og evt. køles. Muligt udslip af CO_2 fra fangstanlæg i forbindelse med lækage vurderes derfor typisk at være begrænset. Det bør dog også vurderes for de konkrete anlæg.

For de fangstanlæg, hvor der sker en kondensering af CO_2, kan køleenheden indeholde ammoniak (NH_3), hvilket i dansk sammenhæng kan betyde, at anlægget bliver omfattet af Risikobekendtgørelsen.

Afvikling af et CO_2 fangstanlæg vil skulle forberedes og effektueres som for andre typiske industri-/procesanlæg, og der er ikke via de internationale erfaringer identificeret væsentlige specifikke sikkerheds-, miljø- og naturmæssige forhold.

3.3 CO_2-mellemlager - sikkerhed, miljø og natur

Mellemlager-faciliteter vil typisk skulle etableres i nærheden af CO_2-punktkilder og -fangstanlæg og på eller i umiddelbar nærhed af havne- og/eller industriområder, hvor transport med skib er mulig. Mellemlager-faciliteter vil formentlig omfatte kondensering / liquefaction-faciliteter og lagring i tanke.

Lagerkapaciteten på mellemlageret vil typisk afhænge af lastbilernes eller skibenes cyklustid.

Det skal i forbindelse med planlægning sikres, at den valgte placering sker under hensyn til de risiko-, miljø- og naturmæssige forhold, som gælder på den enkelte lokalitet. Det nødvendige plangrundlag skal tilvejebringes, og de nødvendige tilladelser indhentes.

Specielt de sikkerhedsmæssige forhold, det vil sige risiko for større udslip af CO_2, skal vurderes. I det norske Northern Lights projekt[2] er der for mellemlageret beregnet stedbunden risiko for området omkring, som er holdt op imod acceptkriterier for forskellig anvendelse. Det vil være relevant at udføre noget tilsvarende for fremtidige, større mellemlagre i Danmark.

Det skal anføres, at der ikke i de internationale referencer er fundet eksempler på uheld med større udslip af CO_2 fra CO_2-mellemlagre.

Anlæg, etablering, drift og afvikling af CO_2-mellemlagre vil foregå som andre typiske industri-/procesanlæg. I drift vurderes de væsentligste miljømæssige forhold at være støj og trafik til og fra anlægget.

---

[2] Northern Lights Projektet (NLP) er en del af det norske Langskip CCS projekt. NLP omfatter skibstransport af CO_2 fra punktkilder til mellemlager, CO_2-mellemlager i tanke, en offshore rørledning ud til en undersøisk satellit, hvor der sker injektion af CO_2 i undersøisk lager.

For de mellemlagre, hvor der sker en kondenseringen af CO_2, kan køleenheden indeholde ammoniak (NH_3), hvilket i dansk sammenhæng kan betyde at anlægget bliver omfattet af Risikobekendtgørelsen og at der herudover kan være risiko for spild, eller udslip af ammoniak.

Naturpåvirkningen ved etablering og drift af mellemlagerfaciliteter vil afhænge af anlæggets placering i forhold til eksisterende sårbar natur og vil primært være relateret til et arealbehov og eventuel inddragelse af beskyttede eller sårbare naturtyper samt til forstyrrelse af beskyttede arter, som følge af fysiske indgreb, trafik og støj.

3.4 CO_2 geologisk lagring – sikkerhed, natur og miljø

Et geologisk lager består af en række elementer:

- et reservoir, dvs. et geologisk lag/ bjergart med en vis porøsitet, f.eks. en sandsten
- en "cap rock"/forsegling, dvs. en impermeabel bjergart som f.eks. lersten og
- en lukning, dvs. en afgrænsning af reservoiret i geologiske strukturer som f.eks. antiklinaler/ domer, forkastningsblokke (forskudte jordlag) eller stratigrafiske afgrænsede lag.

Når CO_2 injiceres i et reservoir, vil det presse formationsvandet væk og bevæge sig ind i porerummet på bjergarten.

For at sikre at CO_2 forbliver i væskefase må det opbevares ved tryk større end dets kritiske tryk som er 73,9 bar, hvilket vil sige i en minimumsdybde på ca. 800 m.

I reservoiret er der 4 mekanismer, der arbejder sammen for at "fange" CO_2.

1) en strukturel fælde,

2) kapillær fangst dvs. CO_2 bliver immobiliseret i porerummet,

3) opløsning af CO_2 i formationsvandet, samt

4) reaktion mellem opløst CO_2 og bjergartsmineralerne, hvorved nye mineraler dannes.

CO_2 lagrene ved Sleipner Vest og Snøhvit i Norge er eksempler på offshore CO_2 sandstenslagre, som er sammenlignelige med nogle af de potentielle danske lagre i Nordsøen.

Udtømte olie- og gasfelter kan potentielt også anvendes som kommende CO_2-lagre. Fordelen ved dem er, at det allerede er bevist, at forseglingen virker over geologisk tid, og at der eksisterer en stor mængde data og viden om reservoiret. Yderligere er der et potentiale for brug af eksisterende infrastruktur.

Indsamling af seismiske data og boringer er en fundamental del af forundersøgelserne for at forstå tilstedeværelsen, udbredelsen og kvaliteten af geologiske lagre.

Offshore foregår seismisk dataindsamling med specialbyggede seismiske skibe. Til lands benyttes typisk vibratorlastbiler til at udsende lydbølger, som opsamles af geofoner på overfladen. For at påvise type af bjergart og undersøge egenskaberne af reservoir og forsegling kræves tillige boring af en brønd.

I forbindelse med injektion skal en ny brønd bores eller en eksisterende boring konverteres til CO_2-injektion.

CO_2 er korrosiv og internationale erfaringer viser, at den vigtigste grund til at injektionsbrønde fejler skyldes, at der er brugt konstruktionsmaterialer, som ikke er tilpasset CO_2. Bekymringerne er typisk rettet mod cementen og eventuel reaktion med CO_2.

Risikofaktorer ved boring er også, at man ved boring rammer lommer af kulbrinter i form af olie eller gas eller lommer af naturligt forekommende CO_2, som kan resultere i et blowout. Sandsynligheden vurderes som lav, og der er ikke identificeret internationale eksempler på sådanne uheld i forbindelse med boring til geologisk CO_2 lagring. Samtidig vil der i dansk sammenhæng forud for eventuelle boringer skulle udføres seismiske undersøgelser, som vil give information om eventuel forekomst af olie, gas og CO_2 i undergrunden. Yderligere er der ikke kendskab til naturligt forekommende CO_2 i dansk undergrund.

Driften af selve CO_2 lageret består af injektion af CO_2 og monitering af reservoiret både til havs og på land. For selve reservoiret og forseglingsbjergarten gøres det med seismiske undersøgelser. Også andre metoder benyttes, f.eks. mikrogravimetriske undersøgelser, hvor ændringer af tyngdeforholdene måles, idet CO_2 er lettere end det saline vand.

På land er monitering af CO_2's mulige indtrængning i grundvandet også nødvendigt. Monitoreringen består typisk af et antal overvågningsboringer, hvorfra der kan indsamles flowdata og tages jævnlige vandprøver.

Der er ikke fundet eksempler på uheld og større udslip af CO_2 fra geologiske CO_2 lagre, ej heller store udsivninger på grund af migrering af den oplagrede CO_2. Det vurderes, at netop godt kendskab til lageret og dets egenskaber, løbende monitorering samt placering i områder med lav tektonisk aktivitet betyder, at der er meget lav risiko for større udslip af CO_2.

Internationale erfaringer rapporterer om fortsat overvågning efter injektionsbrønden er afviklet. Monitorering udført fra 1996 og frem til 2017 af CO_2 udledning fra Sleipner og også på andre lagre har alle vist, at CO_2 forbliver sikkert i lageret.

De væsentligste miljømæssige påvirkninger identificeret via de internationale erfaringer for geologisk lagring offshore omfatter udledninger til vand af kemikalier, boremudder, borespåner og cement mv. i forbindelse med boring og etablering af brønde samt støj, emissioner og energiforbrug fra skibe og borerig i forbindelse med forundersøgelser og anlæg og etablering.

De miljømæssige forhold i forbindelse med anlæg og etablering af geologisk lager på land vurderes ikke at være meget anderledes end de forhold, som er beskrevet for et offshore lager. Den store forskel er, at anlæg og etablering sker på land med landgående maskiner og transportmetoder. Det betyder, at der i langt højere grad vil være risiko for påvirkning af mennesker i umiddelbar nærhed af site. Samtidig vurderes f.eks. affald og spild at udgøre en mindre miljømæssig påvirkning, idet der på land kan ske en kontrolleret opsamling og håndtering.

Drift af geologisk lager indbefatter injektion af CO_2 i lageret, vedligehold af brønd samt monitorering af lageret. De væsentligste miljømæssige påvirkninger fra drift inkluderer: Diffus udledning af CO_2 fra ventilering, tryksatte koblinger mv, støj fra udstyr, udledning af kemikalier samt energiforbrug og emissioner.

I forhold til påvirkning af natur er der i de internationale referencer fokus på udførelse af seismiske undersøgelser, specielt offshore. På land anvendes store og tunge køretøjer, der kan sætte aftryk i landskabet, beskadige vegetation og det øverste jordlag. Der kan også være tale om forstyrrelser af fugle- og dyrevildt samt øvrige beskyttede arter. Påvirkningerne er midlertidige og kan undgås eller mindskes ved planlægning af undersøgelserne og passende afværgeforanstaltninger.

Seismiske undersøgelser på havet kan påvirke fisk og marine pattedyr i form af høreskader og forstyrrelser, som kan medføre undvigeadfærd eller påvirke fødesøgning. Det vurderes, at den skadelige påvirkning af fisk og pattedyr som følge af seismiske undersøgelser og overvågning medfører en lokal, midlertidig påvirkning, som kan reduceres med passende afværgeforanstaltninger.

Ud over de seismiske undersøgelser giver øvrig støjpåvirkning, f.eks. fra skibstrafik og anlægsarbejde en tilsvarende påvirkning af fisk og marine pattedyr. Påvirkningen fra seismiske undersøgelser i et konkret projekt, skal derfor vurderes kumulativt med øvrig støjpåvirkning og ses i sammenhæng med øvrige marine påvirkninger i samme influensområde. Afværgeforanstaltninger som medfører, at marine pattedyr skræmmes væk fra et område, forudsætter eksempelvis, at der er upåvirkede områder i nærheden.

Ved etablering og placering af anlæg, brønde og rørledninger, vil der yderligere være en permanent påvirkning af havbunden og mere midlertidige påvirkninger af marin natur som følge af sedimentspredning, støj, lys, udledning af kemikalier og andre fysiske forstyrrelser.

Herudover afhænger de naturmæssige påvirkninger både offshore og på land af en konkret vurdering og af lokaliteten. Herunder nærheden til f.eks. § 3 lokaliteter, truede arter og beskyttede områder.

Studier vedr. konsekvenser af CO_2-udslip i havet konkluderer, at CO_2 gasbobler opløses inden for et par meter og at forsuring/fald i pH-værdi forsvinder inden for 1 km. Fisk og skaldyr kan blive påvirket ved konstante udledninger og lav pH-værdi, som over tid kan opløse kalkskaller og muslinger. De natur- og miljømæssige påvirkninger af udslip vurderes samlet set som små, også ved potentielle udslip fra flere CO_2-lagre.

Det understøttes også af vurderinger lavet i forbindelse med norske projekter, hvor det er vurderet at et større udslip vil give en ubetydelig påvirkning af det marine miljø. Dette er begrundet i typen af uheld, hvor der er tale om et akut udslip med begrænset spredningsområde, og at CO_2 forventes at blive fortyndet hurtigt i vandmasserne.

I konkrete vurderinger af udsivning og udslip af CO_2 fra lagring eller transport til havs, vil det skulle indgå i vurderingen, at CO_2 i forvejen findes i havet i fluktuerende koncentrationer, og at de marine økosystemer derfor er forholdsvis robuste over for mindre udsving. Samtidig optages i havene fortsat CO_2 fra atmosfæren i så store mængder, at der sker en løbende forsuring. Vurderingen af et konkret projekt vil derfor både skulle indeholde en vurdering af risikoen for en lokal marin påvirkning og en vurdering af formålet og effekten af CO_2-lageret, som er med til at mindske stigningen af CO_2 i atmosfæren og dermed mindske omfanget af den generelle forsuring.

Ved udsivning og udslip af CO_2 på land kan det forventes, at der vil være den samme risiko for toksisk påvirkning af pattedyr, som for mennesker, ved indånding af høje koncentrationer af CO_2 som beskrevet i afsnit 5.1. Konsekvensafstandene er lokale, men kan dog variere afhængig af giftigheden for de enkelte arter. Ekstreme kuldepåvirkninger som følge af et uheld, kan også ramme andre levende organismer end mennesker og vil kunne medføre alvorlig skade og død. Kuldepåvirkninger vurderes ikke at være en relevant effekt ved udslip under vand.

3.5 CO_2-transport infrastruktur

Transport af CO_2 kan ske som en komprimeret gas eller på væskeform. CO_2 transporteres som gas under højt tryk i rørledninger, samt ved mellemtryk og nedkølet som væske i tanke.

Der findes mere end 3.000 km CO_2-rørledninger i Nordamerika, ca. 135 km flerfase rørledning til Snøhvit feltet i den norske del af Nordsøen og ca. 80-100 km CO_2-rørledning på land mellem Rotterdam og Amsterdam. Rørledningstransport af CO_2 og andre gasser under tryk er således en moden kommercielt tilgængelig teknologi.

Rørledninger vil være relevant ifm. transport af store mængder CO_2, f.eks. fra større punktkilder til eksportterminaler samt fra mellemlager videre til lagring i undergrunden. Der findes flere designstandarder for CO_2-rørledninger, se blandt andet DNV-RP-J202 og ISO 27913:2016.

Skibe vil være relevant for transport af større mængder CO_2 på flydende form, over længere afstande. Dette kan f.eks. være transport fra store punktkilder til mellemlagringsfaciliteter eller fra mellemlagringsfaciliteter videre til offshore lagring.

Transport af CO_2 på lastbil eller i godsvogne sker i flydende form svarende til skibstransportforholdene. Vej- og banetransport af CO_2 vil være relevant for små til mellemstore mængder, f.eks. fra små punktkilder til CO_2-anvendelsesfaciliteter eller eksportterminaler. Typisk kapacitet for en lastbil er 25–30 ton CO_2. Ved transport med lastvogn, tog eller skib gælder de internationale transportregler for CO_2 i henhold til ADR[3], RID[4] og IMDG[5].

Der er via en artikel på en amerikansk nyhedsplatform identificeret et uheld med udslip fra en CO_2-rørledning i USA i februar 2020. Ud fra artiklen er der tilsyneladende tale om et rørbrud på en nedgravet rørledning forårsaget af forskydninger i jorden efter meget regn. Uheldet har angiveligt ikke forårsaget dødsfald.

Der er ikke fundet internationale referencer, der specifikt beskriver de miljømæssige påvirkninger under anlæg, etablering og drift af ny rørledning for CO_2. De miljømæssige forhold vurderes at være tilsvarende dem, som identificeres for typiske øvrige rørledninger anvendt til f.eks. transmission og distribution af naturgas.

Dette dækker følgende miljøpåvirkninger, der skal overvejes i de konkrete tilfælde: Støv og øvrige emissioner til luft knyttet til anlægsarbejdet, brug af ressourcer, eventuel udledning af overfladevand eller vand fra grundvandssænkning (kun på land), brug og udledning af kemikalier ved klargøring og drift, CO_2 aftryk samt generering af støj primært ved anlæg.

Ved etablering af CO_2-rørledninger til havs, kan der endvidere være en fysisk påvirkning af havbunden og mere midlertidige påvirkninger af marin natur som følge af sedimentspredning, støj, lys, udledning af kemikalier og andre fysiske forstyrrelser. Udledning af mindre mængder kemikalier i forbindelse med drift af rørledninger er vurderet som ubetydelig i de udenlandske referencer.

[3] ADR: Konvention om International Transport af Farligt Gods ad Vej

[4] RID: Reglementet for international jernbanetransport af farligt gods

[5] IMDG: International Maritime Dangerous Goods Code

Miljø- og naturpåvirkninger fra skibstransport vil være relateret til støj og forstyrrelser samt energiforbrug og tilhørende forbrændingsemissioner og CO_2 aftryk. Herudover kan der være mindre diffus udledning af CO_2 fra tanke og koblinger.

Der er ikke identificeret referencer, der specifikt beskriver miljøforhold ved lastbil og godtogstransport af CO_2. Miljøpåvirkningen fra driftsfasen vil være relateret til støj og forstyrrelser samt energiforbrug og tilhørende forbrændingsemissioner og CO_2 aftryk. Herudover kan der forekomme mindre diffus udledning af CO_2 fra tanke, koblinger mv.

4 Oversigt over relevante internationale projekter

For at indkredse relevante anlæg og projekter, hvorfra erfaringer kunne være relevante er der nedenfor lavet en oversigt over internationale CCS-anlæg inkl. pilot og testanlæg samt projekter på bedding.

I Tabel 1 er listet 27 CCS projekter som er i fuldskaladrift i 2021 inklusiv ét som har været i drift, men er midlertidig nedlukket [2], [4], [5], [6]. I det omfang oplysninger foreligger, fremgår fangstanlæggets størrelse, type af punktkilde, fangstmetode samt transportmetode og lagertype af Tabel 1.

Tabel 1: Oversigt over fuldskala CCS-anlæg i kommerciel drift [2], [4], [5], [6], [7], [8]

Navn	Produktion/år	Beskrivelse
Al Reyadah Carbon Capture, Use, and Storage (CCUS) Project, Abu Dhabi, UAE	Jern og stålproduktion /2016	Separation af CO_2 fra røggas fra jern- og stålproduktion. Separation sker vha. aminbasert fangstmetode med aminen MDEA med en kapacitet på 0,8 Mtpa. CO_2 transporteres via rørledninger til Abu Dhabi National Oil Company og bruges til EOR.
Air Products Steam Methane Reformer ved Valero Refinery i Port Arthur, Texas, USA	Hydrogen produktion /2013	Separation af CO_2 fra syngas ved SMR (steam methane reforming) produktion af hydrogen. CO_2-fangst sker via ved hjælp af VSA (vacuum swing adsorption) med en kapacitet på 1 Mtpa. CO_2 transporteres via rørledninger til EOR i Texas.
Quest (Shell), Alberta, Canada	Hydrogen produktion/ 2015	Separation af CO_2 fra HMU (hydrogen manufacturing unit) til produktion af hydrogen. CO_2-fangst sker via ADIP-X processen (amin absorption) med en kapacitet på 1 Mtpa. CO_2 transporteres via rørledning til geologisk lagring onshore. I sommeren 2020 er 5 mill. ton injiceret.
Karamay Dunhua Oil Technology CCUS, Xinjiang, Kina	Methanol produktion / 2015	Separation af CO_2 fra procesgas. CO_2-fangst sker angiveligt vha. oxyfuel-processen (oplysningerne er sparsomme), med en kapacitet på 0,1 Mtpa. CO_2 transporteres med lastbil til et oliefelt og bruges til EOR.
Arkalon Ethanol, Kansas, USA.	Ethanol produktion / 2009	Separation af CO_2 fra procesgas. CO_2-fangst sker sandsynligvis ved fysiske teknikker (kondensering/komprimering), men ingen sikre oplysninger, med en kapacitet på ca. 0,2 Mtpa. Transporteres via rørledning og anvendes til EOR.
Illinois Industrial Carbon Capture and Storage, Decateur, Illinois, USA	Ethanol produktion / 2017	Separation af CO_2 fra procesgas. CO_2-fangst sker vha. aminbaseret metode (Alstom) med en kapacitet på ca. 1 Mtpa. CO_2 injiceres i et onshore lager direkte under industriparken. Lager: salin sandstens reservoir, dybde 1.980 m
Bonanza BioEnergy, Kansas, USA	Ethanol produktion /2011	Separation af CO_2 fra procesgas. CO_2-fangst sker sandsynligvis ved fysiske teknikker (kondensering/komprimering), men ingen sikre oplysninger, med en kapacitet på ca. 0,1 Mtpa.

Navn	Produktion/år	Beskrivelse
		CO_2 anvendes til EOR i Stewart Oil Field. Transport via rørledning.
Core Energy, Otsego County, Michigan, USA.	Rensning af shale gas /2016	Separation af CO_2 fra shale gas udvinding. CO_2-fangst sker via amin adsorption med en kapacitet på 0,5 Mtpa. CO_2 injiceres i et onshore lager som tidligere var et EOR oliefelt (Niagaran Reef Complex). Transport via rørledning.
Qatar Petroleum, LNG CCS, Qatar	Naturgas opgradering /2019	Separation af CO_2 fra naturgas. CO_2-fangst sker med en kapacitet på 2.1 Mtpa.
Petrobras Santos Basin Pre-Salt Oil Field CCS, Brasilien	Naturgas opgradering /2011	Separation af CO_2 fra naturgas. CO_2-fangst sker vha. membranteknologi. CO_2-fangst sker på en flydende produktionsenhed og anvendes i EOR i Santos Basin Pre-Salt. Direkte injektion fra offshore produktionsfacilitet.
PCS Nitrogen, Louisiana, USA	Gødningsproduktion	Separation af CO_2 fra procesgas. CO_2-fangst med en kapacitet på op til 0,3 Mtpa. CO_2 anvendes til EOR. Transport er ikke oplyst.
Gorgon Carbon Dioxide Injection, Australien	Naturgas opgradering /2019	Separation af CO_2 fra naturgas. CO_2-fangst med en kapacitet på 3,4-4 Mtpa. CO_2 er lagret i et onshore lager på Barrow Island. Transport til lager sker i rør. Lager: salin sandstens reservoir, dybde 2.300m
Alberta Carbon Trunk Line (ACTL) with North West Redwater Partnership's Sturgeon Refinery CO_2 Stream, Canada	Olieraffinering / 2020	Separation af CO_2 fra naturgas mv. CO_2-fangst med en kapacitet på 1,3-1,6 Mtpa. CO_2 anvendes til EOR. Transport til lager sker i rør ACTL.
Alberta Carbon Trunk Line (ACTL) with Nutrien CO_2 Stream, Canada	Gødningsproduktion / 2020	Separation af CO_2 fra procesgas. CO_2-fangst med en kapacitet på 0,3 Mtpa. CO_2 anvendes til EOR. Transport til lager sker i rør ACTL.
Coffeyville Gasification Plant, Kansas, USA	Gødningsproduktion / 2013	Separation af CO_2 fra procesgas. CO_2-fangst med en kapacitet på 1 Mtpa. CO_2 anvendes til EOR på North Burbank oil unit, Oklahoma, US. Transport til lager ikke oplyst.
Enid Fertilizer, Oklahoma, USA	Gødningsproduktion / 2013	Separation af CO_2 fra procesgas med en kapacitet på 0,7 Mtpa. CO_2 anvendes til EOR i oliefelter i Oklahoma. Transport til lager sker i rør.
Boundary Dam 3 Carbon Capture and Storage Facility, Saskatchewan, Canada	Kulfyret energianlæg/2014	Separation af CO_2 fra røggas. CO_2-fangst sker vha. Shell Cansolv teknologi som er aminbaseret med en kapacitet på 1 Mtpa. Hovedparten anvendes til EOR i Weyburn Oil Unit. En mindre dels sendes til geologisk lagring i det nærliggende onshore lager Aquistore Project.
Century plant, Denver, USA	Naturgas opgradering /2010	Separation af CO_2 fra naturgas. Kapacitet på 5-8,4 Mtpa. CO_2 anvendes til EOR i Permian Basin. Transport til lager sker i rør.

Navn	Produktion/år	Beskrivelse
Great Plains Synfuels Plant and Weyburn-Midale; Saskatchewan, Canada	Syntetisk naturgas/ 2000	Separation af CO_2 fra naturgas/procesgas. CO_2-fangst sker vha. Rectisol, proces med en kapacitet på 3 Mtpa. CO_2 anvendes til EOR i Weyburn Oil Unit og Midale Oil Unit. Transport til lager sker i rør.
Sinopec Zhongyuan Carbon Capture Utilization and Storage, China	Petrokemisk produktion/ 2006	Separation af CO_2 fra naturgas/procesgas med en kapacitet på 0,1 Mtpa. CO_2 anvendes til EOR Zhongyuan oil field. Transport er ikke oplyst.
Sleipner, Norge	Naturgas opgradering /1996	Separation af CO_2 fra naturgas. Fangstanlægget er placeret på platform offshore. CO_2-fangst sker vha. aminbaseret metode (MDEA) med en kapacitet på 0,85 Mtpa. CO_2 injiceres i et offshore geologisk sandstenslager ved Sleipner, ud for Norge I alt 17 Mt er injiceret til lageret siden 1996. Lager: salin sandstens reservoir på 1.000m dybde.
Snøhvit, Norge	Naturgas opgradering /2008	Separation af CO_2 fra naturgas. Fangstanlægget er placeret på øen Melkøya, hvor der sker en opgradering af gas fra offshore installation. CO_2-fangst sker vha. aminbaseret metode med en kapacitet på 0,7 Mtpa. CO_2 injiceres i et offshore geologisk lager ved Snøhvit feltet. Transport sker i rør. I alt 4 Mt er injiceret til lageret siden 2008. Lager: salin sandstens reservoir, dybde 2.550m
Terrell Natural Gas Processing Plant , USA	Naturgas opgradering /1970	Separation af CO_2 fra naturgas med en kapacitet på 0,4-0,5 Mtpa. CO_2 anvendes til EOR . Transport sker via rørledning Canyon Reef Carriers CRC pipeline og Pecos pipeline.
Uthmaniyah CO_2 - EOR Demonstration, Kingdom of Saudi Arabia	Naturgas opgradering /2015	Separation af CO_2 fra naturgas med en kapacitet på 0,8 Mtpa. CO_2 anvendes til EOR ved Ghawar oil field. Transport sker via rørledning.
CNPC Jilin Oil Field CO_2-EOR, Kina	Naturgas opgradering /2018	Separation af CO_2 fra naturgas. CO_2-fangst sker vha. aminbaseret metode med en kapacitet på ca. 1,2 Mtpa. CO_2 anvendes til EOR i on-shore ved Jilin oil field i det nordøst lige Kina. Transport sker via rørledning.
Shute Creek Gas Processing Plant, Wyoming, USA	Naturgas opgradering /2018	Separation af CO_2 fra naturgas. CO_2-fangst sker vha. Selexol med en kapacitet på ca. 7 Mtpa. CO_2 anvendes til EOR i en række felter i Wyoming og Colorado. Transport sker via rørledning.
Petra Nova Carbon Capture, Texas USA	Kulfyret energianlæg/ midlertidig lukket i 2020	Separation af CO_2 fra røggas. CO_2-fangst sker vha. aminbaseret metode med en kapacitet på 1,4 Mtpa. CO_2 anvendes til EOR i West Ranch oil field nær Houston.

Som det fremgår af Tabel 1 sker CO_2-fangst både på industrielle kilder, i forbindelse med naturgasopgradering og på energianlæg. CO_2-fangst sker vha. mange forskellige metoder. De projekter som anvender aminvask og chilled ammonia vil være relevante, at hente erfaring fra i denne sammenhæng.

I langt de fleste CCS projekter anvendes den opsamlede CO_2 til enhanced oil recovery (EOR) og bliver dermed sendt retur i eksisterende oliefelt med henblik på at øge udvinding af olie. En del af den CO_2 der er injekseret vil blande sig med råolien og dermed komme retur i forbindelse med den efterfølgende olieudvinding. Der er således ved EOR ikke tale om en permanent lagring af CO_2. Erfaring fra projekter med EOR kan dog være relevant i forhold til andre led i CCS kæden f.eks. i forhold til CO_2-fangst og -transport.

Transport af CO_2 sker i langt overvejende grad via rørledning på land. Det er ikke altid helt klart om rørene i de specifikke projekter er lagt specifikt til CO_2 transport, eller om det er rør, som tidligere har været anvendt til transport af f.eks. gas. Kun i et tilfælde (Snøhvit projektet) transporteres CO_2 vha. rørledning fra land til offshore lager.

Udover ovenstående fuldskala CCS projekter i kommerciel drift er der eller har der været en række pilot- og testprojekter. Nedenfor er kort beskrevet et uddrag af primært europæiske pilot- og test projekter.

Pilot- og testprojekter har oftest omfattet CO_2-fangst, for at eftervise egnethed af en specifik fangstmetode på en specifik kilde. I enkelte tilfælde har projekterne omfattet hele CCS kæden.

Pilot- og testprojekterne kan som de kommercielle anlæg bidrage med erfaringer omkring sikkerhed, miljø og natur selvfølgelig afgrænset i forhold til projekternes omfang, levetid og formål.

Tabel 2: Oversigt over pilot- og testanlæg [4], [9]

Navn	Produktion/år	Beskrivelse
Brindisi CO_2 Capture Pilot Plant, Brindisi, Italien	Kulfyret kraftværk / 2010-2012	Et pilot CO_2-fangstanlæg til test af amin absorption. Kapacitet 2,5 t CO_2 per time. CO_2 lagres i tanke med henblik på brug i et andet pilotforsøg med oplagring i Norditalien.
Buggenum Carbon Capture (CO_2 Catch-up) Pilot Project, Buggenum, Holland	Energianlæg /2011 og 2013.	Et pilot CO_2-fangstanlæg til test af pre-combustion CO_2-fangst. Der bruges water-gas shift efterfulgt af CO_2-absorption i DPEG (dimethylæter polyethylene glykol).
CASTOR, Danmark	Kulfyret energianlæg / 2006 and 2007	Et pilot CO_2-fangstanlæg til test af forskellige aminer.
CESAR, Danmark	Energianlæg, 2008	Opfølgning på CASTOR projektet med modifikation af pilotanlægget og test af to nye aminer.
CO_2 Capture Test Facility at Norcem Brevik, Norge	Cement produktion	Test af CO_2-fangst på røggas fra cement produktion på Norcem Brevik med tre forskellige post combustion teknologier. Testprogrammet

Navn	Produktion/år	Beskrivelse
		blev udført med det formål at udvælge og beslutte egentlig fuldskala projekt.
Schwarze Pumpe Oxy-fuel Pilot Plant, Tyskland	Kulfyret energianlæg	Test af oxyfuel CO_2-fangst på kulfyret energianlæg. Anlægget blev startet op i 2008 og stoppede i 2014. En lille del af den opfangede CO_2 blev injiceret i Ketzin storage site.
Drax bioenergy carbon capture pilot plant, UK	Biomassefyrede energianlæg	Test af CO_2-fangst anlæg på det 100% biomasse fyrede Drax energianlæg. Pilotanlægget startede i 2019.
Technology Centre Mongstad (TCM), Norge	Diverse	Technology Centre Mongstad TCM er lokaliseret ved raffinaderiet i Mongstad, ikke langt fra Bergen og har været i drift siden 2012. Faciliteten har testanlæg for CO_2-fangst med både chilled ammonia og amin.
Lacq CCS Pilot Project, Pau, Frankrig	CO_2 lager onshore	Omkring 51.000 tons CO_2 blev over en periode på 39 måneder opsamlet og injiceret ved brug af et oxyfuel anlæg. Monitorering af lager blev udført både under og 3 år efter injektion. Lager :dolomitisk udtømt gas reservoir, dybde 4.500m
Ferrybridge Carbon Capture Pilot (CCPilot100+); UK	Energianlæg, biomasse og kulfyret	Test af post combustion aminbaseret CO_2-fangstanlæg på røggas fra energianlæg. Testprogram var fuldført i december 2013.
Renfrew Oxy-fuel (Oxycoal 2) Project, UK	Energianlæg	Test af en 40-MWth oxy-fuel burner på energianlægget Renfrew, Scotland.
Mountaineer Validation Facility, USA	Energianlæg	CO_2-fangst vha. af chilled ammonia metoden fra et kulfyret anlæg. CO_2 blev lageret i permanent geologisk lagring onshore. ca. 37.000 ton CO_2 er injiceret i lageret. Injektion til lageret stoppede i 2017 og følges op af 6 års post-injektions monitorering.
Preem raffinaderi i Lysekil, Sverige	Raffinaderi	Største testanlæg i Sverige. CO_2-fangst sker på Preems hydrogen gas anlæg med amin baseret anlæg fra Aker . Det er meningen at CO_2 skal transporteres til lager i Norge som en del af Northern Lights projektet.

Nedenfor fremgår CCS-projekter på bedding, som giver et godt indblik i forestående projekter. I forhold til erfaringer ligger der for nogle af projekterne forundersøgelser og, eller miljøvurderinger, som kan bidrage til det samlede erfaringsbillede indenfor sikkerhed, miljø og natur.

Tabel 3: Oversigt over kommercielle projekter i udvikling [4]

Navn	Projektstadie	Beskrivelse
ACT Acorn, Skotland	Tidlig udvikling	Ideen med projektet er at opsamle CO_2 fra en naturgasterminal ved St. Fergus og sende CO_2 retur til udtømte gasfelter i Nordsøen ved brug af eksisterende gasledninger. CO_2 kilden i St. Fergus er udstødningsgas fra kompressorer til drift af naturgasnettet. CO_2 opsamling ved absorption (sandsynligvis amin).
Caledonia Clean Energy, Skotland	Tidlig udvikling	Idéen med projektet er at Caledonia Clean Energy etablerer et CO_2-fangstanlæg i forbindelse med et nyt gasfyret energianlæg. CO_2-fangst vil være omkring 3 Mtpa. Den opsamlede CO_2 vil skulle transporteres til tømte gaslagre i Nordsøen via eksisterende gasledninger.
HyNet North West,UK	Tidlig udvikling	Idéen med projektet er at etablere CO_2-fangstanlæg i forbindelse med hydrogenanlæg. Den opfangede CO_2 skal sammen med CO_2-fangst fra andre anlæg transporteres til de tømte gasfelter ved Hamilton og Lennox i Liverpool bay.
Langskip CCS - Fortum Oslo Varme,Norge	Moden udvikling	CO_2-fangst på Fortum Oslo Varme affaldsforbrændingsanlæg i en størrelse på 0.4 Mtpa er planlagt til 2024. Den opsamlede CO_2 forventes at blive sejlet med skib til et mellemlager på Norges vestkyst ikke langt fra Bergen og herfra med rør ud til endelig offshore geologisk lager.
Langskip CCS - Nothern Lights projektet	Moden udvikling	NLP er en del af Langskip CCS projektet. Projektet omfatter skibstransport fra punktkilder til mellemlager, mellemlager i tanke, en offshore rørledning ud til en undersøisk satellit, hvor der sker injektion i undersøisk lager. Satellitten vil styres af monitorerings- og kontrolfunktioner fra Oseberg platformen.
Drax BECCS Project, UK	Tidlig udvikling	Idéen med projektet er at etablere et CO_2-fangstanlæg på Drax 660 MW biomassefyrede energianlæg i 2027. Kapacitet på 4,3 Mtpa. Den opsamlede CO_2 planlægges at blive transporteret via rør til endelige geologisk lagring i den sydlige del af Nordsøen.
Ervia Cork CCS, Irland	Tidlig udvikling	Ervia Cork CCS er i undersøgelsesfasen for CO_2-fangst fra punktkilder i Cork, blandt andet to gasfyrede energianlæg og et raffinaderi. Den opsamlede CO_2 skal transporteres via eksisterende rørledninger til Kinsale Gas Field.

5 Sikkerheds- og miljømæssige forhold

Sikkerhed knytter sig til pludselige hændelser, som specifikt har med håndteringen af CO_2 og tilknyttede hjælpestoffer at gøre, og som kan udgøre en fare for menneskers liv og helbred. Hændelserne er på tværs af CCS-kæden i stor udstrækning knyttet til større udslip af kuldioxid CO_2. Herudover kan også udslip af ammoniak, aminer og ilt være relevant for specifikke anlæg. Nedenfor gennemgås de farer som generelt er identificeret ved CCS aktiviteter. I afsnittene 8 - 9 er der anført forhold som er specifikke for de forskellige faser og anlæg.

5.1 Kuldioxid (CO_2)

5.1.1 Indånding af CO_2

CO_2 er en naturlig bestanddel af atmosfærisk luft med en koncentration på ca. 400 ppm eller 0,04%. CO_2 findes i menneskers udåndingsluft i en koncentration på ca. 38.000 ppm eller 3,8%.

CO_2 har en lav akut giftighed for mennesker, men som for alle andre stoffer er CO_2 giftig, hvis koncentrationen er høj nok. Ved udsættelse for en koncentration på mere end 5% stiger blodets CO_2 koncentration og der opstår acidose (faldende pH i blodet). Ved koncentrationer på mere end 10% CO_2 kan der opstå kramper, koma og ved længerevarende udsættelse, i nogle tilfælde død. Ved udsættelse for koncentrationer på mere end 30% CO_2 kan der opstå næsten øjeblikkelig bevidstløshed og død [10]. Udover giftvirkningen vil CO_2 ved et udslip også kunne sænke iltkoncentrationen i et område, så personer kvæles. Ved kendte tilfælde af personer der er døde som følge af udsættelse for CO_2, vil der som regel være tale om en kombination af CO_2 giftvirkning og kvælning på grund af iltmangel.

Faren ved udslip af CO_2 er især kendt fra udslip i lukkede rum, men der er også eksempler på massive udslip fra minegange, hvor personer i almindelige boliger i nærområdet er blevet dødeligt påvirket (Menzengraben, DDR, 1953) [11]. En særlig situation var et massivt udslip af CO_2, anslået 1,6 millioner tons CO_2, fra en bundvending (limnisk udbrud) af søen Lac Nyos i Cameroun i 1986. Der omkom ca. 1.700 mennesker og 3.500 stk. husdyr, i en afstand på op til 25 km fra søen [12].

UK Health and Safety Executive har i flere publikationer estimeret konsekvensafstande for henholdsvis store momentane udslip af CO_2 og for store kontinuerte udslip fra lækager [12], [13], [14]. For momentane udslip blev der studeret udslipstørrelser på 50 – 2.000 tons. Disse udslipstørrelser svarer til variationen i oplagsstørrelse fra tankvogne til større tanklagre.

For de største momentane udslip blev der fundet en konsekvensafstand på 120 – 300 meter. Ved kontinuerte udslip fra en lækage blev der fundet en konsekvensafstand på 100 – 200 meter. Konsekvensafstanden er defineret som den afstand, inden for hvilken, der er en risiko for død på 1-5%. Ved længere afstande fra udslipspunktet er risikoen for død mindre.

Det er rimeligt at antage, at disse afstande er repræsentative for uheld på transportsystemer og lagre fra fangst af CO_2 og indtil injektion i slutlageret.

Et geologisk lager ligger typisk i en dybde på mere end 800 meter under jordoverfladen/havbunden og den eneste direkte forbindelse med atmosfæren/havet er et borerør med en række ventiler. Det er derfor vanskeligt at forestille sig, at store mængder CO_2 fra et geologisk lager kan undslippe momentant og forårsage dødsfald i flere kilometers omkreds, som det har været tilfældet ved de før omtalte udslip fra minegange og fra bundvending af søer. Det kan dog ikke udelukkes at et voldsomt jordskælv eller et vulkanudbrud i et område med geologisk lagring af CO_2 kan frigive store mængder CO_2 til atmosfæren over kort tid. Det må antages, at der ikke placeres geologiske lagre i risikoområder for jordskælv og vulkanudbrud, herudover er der ikke vulkanaktivitet i Danmark og sandsynligheden for større jordskælv er endvidere meget lille grundet placering i forhold til geologiske pladegrænser.

Derimod er store CO_2 udslip fra injektion i geologiske formationer mulige – og kendte – i forbindelse med blowouts [15]. Konsekvensafstanden[6] på 100 meter fra et kontinuert udslip fra en lækage på 50 mm er i førnævnte publikationer fra UK HSE anset for repræsentativ for et blowout, forudsat at udslippet sker til luften. Hvis udslippet sker lige over havbunden, er der ikke umiddelbar fare for mennesker, da den CO_2 der stiger op til overfladen vil fortyndes/optages i vandsøjlen, inden den når atmosfæren [16].

Der er ikke identificeret blowouts fra underjordiske lagre, som er anlagt som deciderede CO_2 lagre.

I ovennævnte kilde [15] anføres fire tilfælde af blowouts i forbindelse med boring i geologiske formationer med henblik på udnyttelse af den naturligt forekommende CO_2 (Sheep Mountain, CO, USA; Crystal and Tenmile Geysers, Paradox Basin, UT, USA; Florina Basin, Grækenland; Torre Alfina geotermisk felt, Italien). I kilden argumenteres for at disse hændelser lige så godt kunne være opstået i forbindelse med anlæg af deciderede CO_2 lagre , og at der bør drages lære af dem.

De ovennævnte konsekvensafstande er udregnet ved hjælp af kommercielt tilgængelige programmer. Der er stillet spørgsmålstegn ved, om disse programmer på tilfredsstillende vis modellerer de komplicerede forhold, når tryksat CO_2 slipper ud i atmosfæren og spredes i omgivelserne, specielt hvad angår effekten af sublimering af dannet tøris [10]. Det kan derfor ikke udelukkes, at der i fremtiden opnås ny viden om spredningsforholdene som vil revidere de konsekvensafstande, der er anført i denne rapport, og som kan få indflydelse på planlægningen omkring installationer med store mængder CO_2.

[6] Konsekvensafstanden er den afstand, ved hvilken risiko for dødsfald er 1-5%

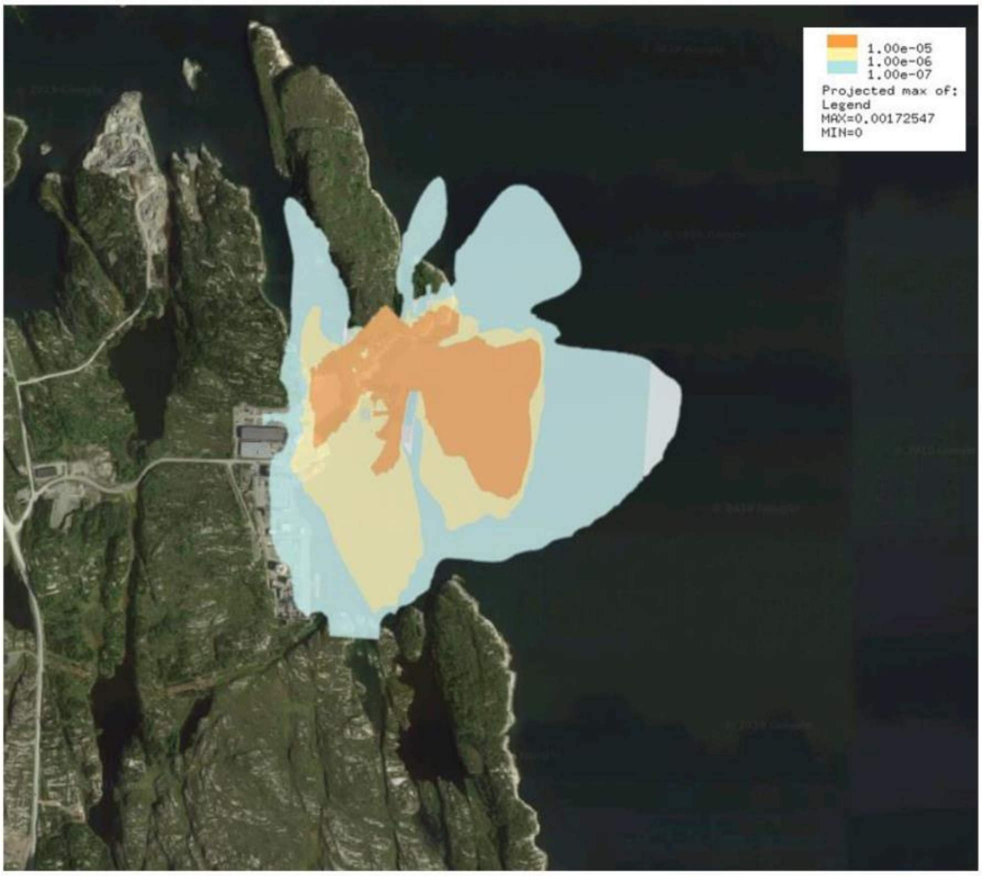
I forbindelse med Northern Lights projektet er der udarbejdet en kvantitativ risikovurdering (QRA) for mellemlageret på land [17].

Ved en QRA sættes de mulige konsekvenser i forhold til sandsynligheden for at de identificerede hændelser indtræffer. Et af resultaterne af en QRA er et kort med konturer omkring den undersøgte facilitet, som viser afstande med den samme risiko for dødsfald for personer, der befinder sig i det pågældende område.

I nedenstående Figur 2 er gengivet et kort for landanlægget ved Northern Lights. I det inderste orange område er der en risiko for dødsfald på 10^{-5} per år (svarende til et dødsfald per 100.000 år), i det gule 10^{-6} per år (svarende til et dødsfald per 1.000.000 år) og i det blå område 10^{-7} per år (svarende til et dødsfald per 10.000.000 år). Disse værdier svarer til de værdier, der anvendes af de danske myndigheder til at afgøre, om risikoen er acceptabel.

Det inderste orange område må som udgangspunkt ikke strække sig ud over virksomhedens matrikel. Ud til grænsen for det gule område må der ikke placeres boliger eller anden følsom anvendelse, og ud til grænsen for det blå område må der ikke placeres institutioner, der indgår i det offentlige beredskab eller findes institutioner med svært evakuerbare personer.

I det aktuelle tilfælde er det vurderet, at de norske myndigheders acceptkriterier, som på mange måder er de samme som de danske, er overholdt. Resultaterne kan dog ikke direkte overføres til et andet projekt, da omgivelsernes topografi er afgørende for udbredelsen af et CO_2 udslip, da der er tale om en kold, tung gas.



Figur 2 *Risikokonturer for et landanlæg i Northern Lights projektet [17]. Den blå markering har en udstrækning på ca. 1 km i øst vestlig retning.*

Store momentane udslip af CO_2 vil også have en effekt på dyre- og planteliv både i vandmiljøet og på land. Konsekvenserne af sådanne udslip på natur og miljø er behandlet i afsnittene om natur og miljø.

5.1.1 Fysiske påvirkninger fra uheld med CO_2

Udover udsættelse for høje koncentrationer af CO_2 kan der ved større udslip også opstå alvorlige skader som følge af ekstreme kuldepåvirkninger. I CCS sammenhæng vil CO_2 efter fangst blive komprimeret og evt. afkølet, før det transporteres og oplagres. Hvis der sker et udslip af komprimeret/afkølet CO_2 fra en rørledning, beholder eller et reservoir, opstår der risiko for ekstreme kuldepåvirkninger for personer eller udstyr som påvirkes af udslippet. Ramte personer kan få alvorlige og livstruende forfrysninger, mens udstyr kan påvirkes, så det mister sin integritet.

Da CO_2 efter fangsten håndteres under tryk, er der mulighed for farlige trykstigninger, som kan føre til sprængning af rør og beholdere med udslyngning af sprængstykker til følge. På denne måde adskiller CO_2 sig ikke fra andre trykbærende systemer, bortset fra at CO_2 ikke kan brænde. Interne eksplosioner på grund af indtrængning af atmosfærisk luft eller brand og eksplosion i undsluppet CO_2, er ikke mulige.

I litteraturen findes oplysninger om en ulykke i Ungarn i 1969, med en 30 m^3 tank indeholdende CO_2, som pludseligt brød sammen [18]. Fragmenter med en vægt på 1 – 3 tons blev slynget væk i en afstand på op til 300 meter og mindre fragmenter op til 400 meter. Ulykken kostede 9 mennesker livet, hvoraf de 5 dødsfald skyldtes forfrysninger. De øvrige dødsfald antages at skyldes de fysiske påvirkninger fra eksplosionen.

I en publikation for det engelske HSE Executive [19] konkluderer forfatterne, at fartøjer i nærheden af et gasudslip ikke kan synke på grund af manglende opdrift. Hvor der er forekommet forlis, skyldes det, at fartøjer har taget vand ind på grund af urolig sø forårsaget af udslippet. Desuden kan et udslip skabe strømninger i overfladen, som kan få opankrede fartøjer ud af position. Publikationen nævner ikke specifikke eksempler, eller hvor ofte det er sket.

Ekstreme kuldepåvirkninger kan også ramme andre levende organismer end mennesker og vil i lighed med påvirkning på mennesker kunne medføre alvorlig skade og død. Kuldepåvirkninger vurderes ikke at være en relevant effekt ved udslip under vand.

5.2 Aminer

Ved nogle fangstmetoder (se også afsnit A.1) bruges forskellige blandinger af aminer. Der er nævnt ethanolamin (MEA), diethanolamin (DEA), metyldietanolamin (MDEA), piperazin (PZ), 2-Amino-2-metylpropanol (AMP), diglykolamin (DGA) og diisopropanolamin (DIPA). Ingen af de nævnte aminer udgør en akut fare for mennesker i vandig opløsning, ved et udslip. Dampene har en lav akut giftighed og aminerne er ikke klassificerede som brandfarlige. Aminerne er generelt irriterende at få på huden og i øjnene, og nogle er klassificeret som ætsende. Håndtering følger de normale arbejdsmiljøregler, og ved udslip vurderes der ikke at være akut fare for mennesker, udover de personer i umiddelbar nærhed af udslippet, som kan blive ramt og få ætsninger, afhængig af aminblandingens karakter, samt evt. forbrændinger, afhængig af temperaturen på udslippet.

De anvendte aminer er ikke klassificeret som miljøfarlige, og der forventes derfor ikke akutte virkninger på natur eller miljø ved udslip.

Nedbrydningsprodukter af aminer, herunder nitrosaminer, afhængig af hvilken aminblanding der benyttes (se også afsnit A.1.3) kan udledes fra CO_2-fangstanlæg. Nitrosaminer har en lav akut giftighed, og der er ved de koncentrationer som forventes ikke fare for akut forgiftning med nitrosaminer. Nitrosaminer og andre nedbrydningsprodukter anses for at være kræftfremkaldende og derfor farlige ved langvarig og gentagen påvirkning. Dette aspekt er behandlet under afsnittet om miljø.

5.3 Ammoniak (NH_3)

NH_3 i form af ammoniakvand kan også bruges til CO_2-fangst. Koncentrationen af NH_3 i ammoniakvandsopløsningen er typisk mindre end 25%. Hvis koncentrationen af NH_3 er højere end 25% skal ammoniakvand betragtes som et risikostof i henhold til Risikobekendtgørelsen, på grund af akut miljøfare. Hvis oplaget af ammoniakvand > 25% er på mere end 100/200 tons skal der derfor udarbejdes sikkerhedsdokument/sikkerhedsrapport. I det følgende forudsættes det, at koncentrationen af NH_3 i ammoniakvand er mindre end 25%.

I brugskoncentrationer på mindre end 25% er ammoniakvand klassificeret som ætsende på hud og øjne og som irriterende for luftvejene og skal håndteres jf. de normale arbejdsmiljøregler for sådanne stoffer. Ved uheld er der ikke akut fare for mennesker, udover de personer i umiddelbar nærhed af udslippet, som kan blive ramt og få ætsninger.

I delstrømme i CO_2-fangstprocessen med ammoniak er der høje koncentrationer af NH_3, i området 2.000 – 15.000 ppm. Disse koncentrationer er livsfarlige for mennesker, idet en udsættelse for 2.700 ppm i 10 minutter (AEGL 3, 10 min) eller længere, anses for livstruende. Processtrømmene findes i lukkede rørsystemer og beholdere, men ved udslip vil der være akut fare for personer der udsættes for høje koncentrationer af NH_3. Umiddelbart vurderes det, at der kun er fare for personer på virksomheden, men hvis denne proces etableres, bør der udføres spredningsberegninger for uheld ved den konkrete anvendelse, for at fastlægge de specifikke konsekvensafstande. NH_3 lukkes ikke urenset ud i atmosfæren, da der typisk indføres et vasketrin, som bringer NH_3 koncentrationen i afkastet ned til under 200 ppm.

Gasformig ammoniak er akut toksisk for levende organismer, der rammes af et udslip, afhængig af koncentrationen. På grund af fortynding vil virkningen være begrænset til områder med høj koncentration af ammoniak. Vandlevende organismer påvirkes ikke af et udslip af gasformig ammoniak. Ammoniakvand i de koncentrationer der typisk anvendes i et fangstanlæg, er ikke klassificeret som miljøfarlig, men der må alligevel forventes lokale akutte effekter, hvis ammoniakvand finder vej til vandmiljøet, ligesom lokal svidning af vegetationen må forventes, hvis ammoniakvand løber ud på jorden.

5.4 Oxygen (O_2)

I forbrændingsanlæg kan oxyfuel processen anvendes i stedet for almindelig forbrænding med atmosfærisk luft. Ved oxyfuel processen tilføres ren O_2 til forbrændingsprocessen i stedet for atmosfærisk luft, som indeholder ca. 80% nitrogen. Herved fås en CO_2-rig røggas som efter tørring har en CO_2 koncentration på 70 – 90% CO_2, som kan komprimeres og anvendes til f.eks. lagring. Til oxyfuel processen er der behov for et lager af O_2, som opbevares i en tryktank. Hvis oplaget af O_2 er større end 200 (kolonne 2) hhv. 2000 tons (kolonne 3), falder oplaget ind under Risikobekendtgørelsens bestemmelser og der skal udarbejdes sikkerhedsdokument/sikkerhedsrapport.

O_2 er en naturlig bestanddel af atmosfærisk luft, hvor den findes i en koncentration på ca. 21%. Som udgangspunkt er O_2 derfor ikke farlig for mennesker. Stiger koncentrationen af O_2 til 25% eller derover er der en stærkt stigende risiko for brand og eksplosion. O_2 er ikke i sig selv brandfarlig, men er en nødvendig forudsætning for en brand, sammen med en passende (høj) temperatur og et brandbart materiale. Visse materialer kan bryde spontant i brand ved normal omgivelsestemperatur, blot O_2 koncentrationen øges.

Indånding af høje koncentrationer af O_2 op til 100% er ikke akut farlig for mennesker og bruges sågar terapeutisk i nogle sammenhænge. Langvarig udsættelse for høje koncentrationer af O_2 er dog sundhedsskadelig, men er ikke relevant i denne sammenhæng.

Uanset om oplaget af O_2 er større end tærskelmængden for risikovirksomhed, bør der i konkrete tilfælde udføres analyser af risikoen for udslip af O_2 og konsekvenserne af disse, i forbindelse med planlægningen.

Udslip af O_2 vurderes ikke at udgøre en fare for natur og miljø.

6 CO_2-fangstanlæg - Vurdering af sikkerhed, natur og miljø

6.1 Sikkerhed

6.1.1 Forundersøgelser

Der er ikke identificeret relevante referencer med omtale af sikkerhedsforhold specifikt relateret til forundersøgelser til etablering af CO_2-fangstanlæg.

6.1.2 Anlæg og etablering

Der er ikke identificeret relevante referencer med omtale af sikkerhedsforhold specifikt relateret til anlæg og etablering af CO_2-fangstanlæg.

6.1.3 Drift

Almindelige farer ved drift af trykbærende udstyr i form af operationelle forhold der kan føre til farlige trykstigninger, er også gældende for CO_2-fangstanlæg.

I forhold til større uheld skal der ved oxyfuel-anlæg være opmærksomhed på risikoen for lækage på tanke og rørsystemer indeholdende store koncentrationer af O_2 og deraf følgende udslip af store mængder O_2 med brand- og eksplosionsfare til følge. Ved chilled ammonia anlæg skal der være opmærksomhed på risikoen for lækage på rørsystemer indeholdende store koncentrationer af NH_3 med forgiftningsfare til følge.

I afsnit 5.3 og 5.4 er der en beskrivelse af de mulige farer og konsekvenser ved håndtering og udslip af O_2 og NH_3.

Udover O_2 og NH_3 som har potentiale til store uheld med lang rækkevidde, skal der også være opmærksomhed på lækager af aminholdige systemer, som kan forårsage ætsninger på personer der rammes af et udslip. I afsnit 5.2 er der en beskrivelse af de mulige farer og konsekvenser ved håndtering og udslip af aminer.

Den stående mængde ren CO_2 i et fangstanlæg er forholdsvis lille, da CO_2 først i forbindelse med mellemlagring komprimeres og evt. køles. Udslip af CO_2 fra fangstanlæg vil derfor være begrænset.

Der er ikke fundet eksempler på uheld med CO_2-fangstanlæg i de undersøgte referencer.

6.1.4 Afvikling

Ved afvikling (nedrivning) af CO_2-fangstanlæg skal der udover de almindelige arbejdsmiljøregler være fokus på, at der ikke findes ansamlinger af stoffer og materialer i anlæggene, som kan udgøre en fare for medarbejderne i forbindelse med nedrivningsaktiviteterne. Ansamlinger af aminer og ammoniakvand udgør her en potentiel risiko. Det vurderes at disse ansamlinger ikke udgør en fare for natur og miljø, forudsat at det vaskevand der anvendes til rengøring af udstyret, håndteres forsvarligt.

Der er ikke fundet eksempler på uheld under afvikling af CO_2-fangstanlæg, i de undersøgte referencer.

6.2 Miljø

6.2.1 Forundersøgelser

Der er ikke identificeret referencer der specifikt beskriver miljøforhold ved forundersøgelser af CO_2-fangstanlæg.

De miljømæssige forhold ved forundersøgelser vurderes at være sammenligneligt med hvad der findes i forbindelse med forundersøgelser ved andre industrielle anlæg.

Det skal i forbindelse med planlægning sikres, at den valgte placering sker under hensyn til de risikomæssige og miljømæssige forhold. Det nødvendige plangrundlagt skal sikres, og de nødvendige tilladelser være indhentet.

6.2.2 Anlæg og etablering

Der er ikke identificeret referencer, der specifikt beskriver miljøforhold ved anlæg og etablering af CO_2-fangstanlæg.

De miljømæssige forhold ved anlæg og etablering vurderes at være sammenligneligt med, hvad der findes i forbindelse med forundersøgelser ved andre industrielle anlæg.

Det omfatter typisk: Støv og øvrige emissioner til luft knyttet til anlægsarbejde, brug af ressourcer, eventuel udledning af overfladevand eller vand fra grundvandssænkning, CO_2 aftryk i anlægsfase samt generering af støj.

6.2.3 Drift

Drift af CO_2-fangstanlæg har en række miljømæssige forhold.

Emissioner til luft

Emission og deposition af aminer og specielt nedbrydningsprodukter af aminer har været en af de primære bekymringer ved udvikling af fuldskala aminbaserede fangstanlæg [20].

De aminbaserede fangstmetoder (se også afsnit A.1) bruger forskellige aminer eller blandinger af aminer. Der er i litteraturen blandt andet nævnt ethanolamin

(MEA), diethanolamin (DEA), metyldietanolamin (MDEA), piperazin (PZ), 2-Amino-2-metylpropanol (AMP), diglykolamin (DGA) og diisopropanolamin (DIPA) [21] [22]. Redegørelse for de enkelte kemiske stoffer kan findes vha. ECHAs hjemmeside [23].

Emissioner til luft og vand samt affald kan indeholde varierende mængder af aminer samt nedbrydningsprodukter af aminer, herunder nitrosaminer og nitraminer, afhængig af hvilken aminblanding der benyttes [24] [22] [25].

Det anføres som en af de væsentligste konklusioner fra Longship projektet, at det er vigtigt have metoder og data på plads for at kunne vurdere emissioner og immissioner af farlige stoffer fra fangstprocessen inklusiv aminer samt eventuelle nedbrydningsprodukter heraf [26].

I Norge har man på CO_2 Technology Center Mongstad (TCM) siden 2012 haft faciliteter til at teste forskellige aminbaserede og chilled ammonia fangst teknologier, og der har været en række leverandører som her har testet, optimeret, modnet og eftervist deres fangst teknologi og valg af solvent. Arbejdet på TCM har også inkluderet udvikling af metoder til bestemmelse og vurdering af emission og deposition fra de aminbaserede fangstmetoder, udover at det har givet bedre forståelse af de toksikologiske effekter af aminer og deres nedbrydnings produkter til luft, vand og via affald [24] [27].

Der rapporteres om stor variation i emission af aminer, nitrosaminer og andre stoffer fra forskellige anlæg og afhængig af den specifikke proces og hvilke aminer der anvendes. Emission af aminer i røggassen er målt i afkast på forskellige pilotanlæg i koncentrationer op til 4 mg/Nm^3. Nitrosaminer og nitraminer er blevet målt i røggassen i koncentrationer op til 5 $\mu g/m^3$. Der er en tendens til at nyere anlæg har en mindre emission [28].

Reaktion af aminer med specielt NO_X er i søgelyset i forhold til dannelse af nedbrydningsprodukter i form af nitrosamin og nitraminer [28].

Aker, der leverer CO_2-fangstanlæg, beskriver at spredningsberegninger udført for Norcem Brevik viser at koncentrationer af nitrosaminer med deres løsning med et specifikt amin og med brug af anti misting teknologi ligger væsentlig under gældende norske grænseværdier [29].

Forsøg fra amin baseret CO_2-fangst på testanlæg i Japan med blandt andet to forskellig aminer viser at en stor del af amin emissionen foreligger som aerosoler (mist) [30]. Også en anden kilde referer til, at aerosoler har en effekt på emissionen af amin [28].

Der har være udført test på Fortum Oslo Varme med et pilotanlæg med Shell capture technology og brug af DC-103 solvent. Resultaterne herfra viser at Fortum Oslo Varme med den teknologi kan leve op til de norske krav for udledning til luft [26].

Det konkluderes i rapport fra det norske Olje- og energidepartement fra 2016 at der er sket en stor udvikling og opnået meget viden og erfaring om de forskellige CO_2-fangstteknologier og de HSE relaterede risici, samt at der er leverandører der er i stand til at levere fuldskalaanlæg [31].

I Norge har Folkhelseinstituttet sat grænseværdier for nitrosaminer og nitraminer i luft (immission) og vand, hvilke har været anvendt i godkendelser af aminbaserede fangstanlæg [32].

I Storbritannien er der Environmental Assessment Levels (EAL's) for nogle aminer men ikke for alle, der anvendes til CO_2-fangst. Arbejdsmiljøgrænseværdier (OEL) findes for aminen "MEA," og det anføres, at den vil kunne bruges til at udvikle en EAL for "MEA" mellem 5 µg/m³ (long-term) and 15,2 µg/m³ (15 minute short-term). Foreslåede sundhedsbaserede grænseværdier for Nitrosaminer ligger mellem 0,07 ng/m³-10 ng/m³.

Det er også på tale at bruge et reference amin (NDMA) på linje med f.eks. hvordan benzo(a)pyrene anvendes som reference i forbindelse med polyaromatiske hydrocaboner (PAH'er).

Det nævnes i samme rapport at den norske EAL på 0,3 ng/m³ (maks værdi) for nitrosaminer og nitraminer (NDMA) ikke kan bruges direkte, da Storbritannien har en anden måde at vurderer kræftfremkaldende stoffer [28].

Der er endvidere i Storbritannien i 2021 udarbejdet et review af Best Available technolgy (BAT) af aminbaserede fangst teknologier til anvendelse på gas og biomassefyrede energianlæg [21] som har resulteret i en BAT-vejledning til brug for anlægsoperatører og myndigheder [33]. I samme forbindelse er der også fastsat EALs for mono-ethanolamine (MEA) og N-nitrosodimethylamine (NDMA).

- MEA EAL for luft: 24 h gennemsnit: 0,1 mg/m³, 1h gennemsnit 0,4 mg/m³
- NDMA EAL for luft: Årligt gennemsnit: 0,2 ng/m³

For chilled ammonia processen er det primært udledning af ammoniak, der skal undgås og kontrolleres. Det anføres, at der findes tilgængelige renseteknologier i tilfælde af eventuelle høje udledningskoncentrationer [25].

Oxyfuel processen vil typisk have en reduceret NO_X emission sammenlignet med forbrændingsprocesser med atmosfærisk luft [34].

I rapport fra anlæg i Lacq anføres ingen væsentlige miljøpåvirkninger fra oxyfuel fangstanlægget [35].

Ved et retrofit af CO_2-fangst på et eksisterende anlæg skal man være opmærksom på, at der vil ske en ændring af røggastemperatur, flow og vandmætning, der influerer emissionskoncentrationer og spredning af røggassen.

I rapport fra International Energy Agency IEA fra 2011 er konklusionen at afhængig af valg af capture teknologi og synergier kan være tradeoffs, hvad angår emission af NO_x, NH_3, SO_2 and PM [20]. Det påpeges at der fra anlæg med

CO_2-fangst ved brug af aminer kan opstå en øget direkte udledning af NO_X og PM, idet effektiviteten af anlægget vil falde. SO_2 emissionen fra anlæg med CO_2-fangst vurderes at falde, idet der er høje krav til SO_2 indhold i røggassen forud for fangstprocessen. NH_3 emission kan forventes at stige for de amin baserede fangst teknologier. For de øvrige fangstteknologier forventes ligeledes tradeoffs.

Udledning af procesvand

Der kan også ske emission af amin og nedbrydningsprodukter via spildevand specielt amintab via spildevand fra scrubbersystemet vurderes at være et opmærksomhedspunkt. Der refereres til målte værdier af nitrosaminer i spildevand i koncentrationer op til 6,79 g/l. Nedbrydelighed af nitrosaminer i vand varierer betydeligt [28].

I Storbritannien foreligger der ikke en grænseværdi for nitrosaminer i vand, idet der ikke foreligger tilstrækkelig data for de økotoksikologiske effekter [28].

For oxyfuel udkondenseres større mængder vand fra røggassen, hvilket dog er tilsvarende ved normal forbrænding. Dette vand skal renses som typisk røggaskondensat.

Støj

Støjkilder på fangstanlæg vil være kompressor, booster sugetræksblæser samt cirkulationspumper på anlægget. CO_2-kompressoren vil skulle placeres i en lydisoleret og ventileret bygning. Der er ikke fundet kilder som nævner støj som en væsentlig miljøpåvirkning fra CO_2-fangstanlæg.

Arker, der leverer CO_2-fangstanlæg, beskriver at der i forbindelse med CO_2-fangstanlæg skal laves passende støjreducerende tiltag [29].

Affaldsprodukter

Reclaimer processen for både aminbaserede og chillede ammonia anlæg vil resultere i affald der skal bortskaffes. Affaldets sammensætning og indhold af farlige stoffer og form vil afhænge af specielt reclaimer processen [36].

Aminaffald er nævnt som en væsentlig miljømæssig påvirkning. Der estimeres 1 kg amin affald per 1 ton CO_2.

Energiforbrug til processen

Amin baseret CO_2-fangst nævnes som en meget energikrævende proces specielt til regenereringsprocessen [29] og tilstedeværelse og brug af "overskudsenergi" fra øvrige processer er vigtig for at holde det samlede energiforbrug nede.

En energianalyse udført på forskellige scenarier for CO_2-fangst på affaldsforbrændingsanlæg i DK nævner ligeledes, at CO_2-fangst kræver en betydelig mængde varme i form af damp til stripperen og det er vigtigt for at få en høj samlet effektivitet at så meget af varme fra CO_2-fangstprocessen genvindes til fjernvarmeproduktion. Ved introduktion af varmepumper kan fjernvarmeproduktionen øges med op til 20 % i forhold til et anlæg uden CO_2-fangst, men til gengæld falder elproduktionen fra ca. 15 MW til ca. 6,5 MW for et anlæg med en affaldsbehandlingskapacitet på 30 ton/h. Det konkluderes, at der er et behov for en afvejning mellem reduktion i produceret elektricitet og en øget varmegenvinding og fjernvarmeproduktion i det konkrete projekt [37].

I rapport fra Det Europæiske Miljøagentur nævnes, at der for det enkelte projekt er behov for at se på hele CCS kæden i et livscyklus perspektiv for at vurdere CO_2 fodaftryk og øvrige emissioner [38].

Det er i samme rapport nævnt at CO_2-fangst på energianlæg samlet set vil betyde et øget energiforbrug på 15-25% til energiproduktion, transport, konditionering og mellemlagring.

Det norske Longship CCS projekt har vurderet, at der skal anvendes ca. 1,2–1,5 MWh/ton CO_2. Omkring 2/3 af energiforbruget er til varme, det øvrige er til el og til brændstof til skibe. Den største andel af energiforbruget bruges til CO_2-fangst og liquefaction.

En livscyklus analyse (LCA) af samme projekt viser at for "worst case" scenariet er CO_2 footprint 0,099 ton CO_2 udledt / ton CO_2 til lager.

I rapport fra IASS [25] nævnes et højt energiforbrug som en miljøpåvirkning for både oxy-fuel og chilled ammonia teknologierne. Herudover nævnes indirekte energiforbrug til NH_3 produktion anvendt i chilled ammonia fangst processen.

I Bref dokumentet (Best Available Techniques (BAT) Reference Document) for store fyringsanlæg er det estimeret, at energiforbruget til CCS vil give anledning til at netto el-effektiviteten reduceres med 8-12% [39].

Øvrige påvirkninger

Aker, der leverer CO_2-fangstanlæg, beskriver at der i forbindelse med CO_2-fangstanlæg skal laves passende tiltag i forhold til reduktion af udledning af varmt vand til recipient [29].

6.2.4 Afvikling

Der er ikke identificeret referencer der specifikt beskriver miljøforhold ved afvikling af CO_2-fangstanlæg.

De miljømæssige forhold ved afvikling vurderes at være sammenlignelige med, hvad der findes i forbindelse med afvikling af andre industrielle anlæg.

Det omfatter typisk: Støv og øvrige emissioner til luft knyttet til afviklingen, affaldsgenerering, eventuel udledning af overfladevand, CO_2-aftryk under afvikling samt generering af støj.

6.3 Natur

6.3.1 Forundersøgelser

Der er ikke identificeret referencer, hvor der fremgår en naturpåvirkning som følge af de undersøgelser, som er nødvendige forud for etablering af CO_2-fangstanlæg.

De naturmæssige forhold ved forundersøgelser vurderes herudover at være sammenligneligt med hvad der findes i forbindelse med andre tilsvarende industrielle anlæg.

6.3.2 Anlæg og etablering

For Lacq fangstanlæg, er der tale om CO_2-fangst fra en eksisterende naturgasproduktion. Det er derfor vurderet i forbindelse med miljøvurdering af projektet, at der ikke er en påvirkning på omgivende flora, fauna og jordbund, da installationerne til CO_2-fangst etableres inden for det eksisterende anlæg [35].

De naturmæssige forhold ved anlæg og etablering vurderes herudover at være sammenligneligt med hvad der findes i forbindelse med andre tilsvarende industrielle anlæg.

6.3.3 Drift

For Lacq fangstanlæg, er det vurderet i forbindelse med miljøvurdering af projektet, at der ikke sker en yderligere påvirkning på omgivende flora, fauna og jordbund eller emissioner, støj og trafik. Overvågning af flora og fauna over en 5-årig periode har ikke vist ændringer i området [35].

Der er ikke identificeret referencer, hvor der fremgår en naturpåvirkning som følge af eventuelt udslip af aminer fra et CO_2-fangstanlæg.

6.3.4 Afvikling

Der er ikke identificeret referencer, som omhandler naturpåvirkningen ved afvikling af et CO_2-fangstanlæg. Det forventes dog, at naturpåvirkningen ved afvikling af fangstanlæg generelt vil svare til påvirkningerne i anlægsfasen og sammenligneligt med tilsvarende industrielle anlæg.

7 Mellemlager faciliteter - Vurdering af sikkerhed, natur og miljø

7.1 Sikkerhed

7.1.1 Forundersøgelser

Der er ikke identificeret relevante referencer med omtale af sikkerhedsforhold specifikt relateret til forundersøgelser til etablering af CO_2-mellemlagre.

7.1.2 Anlæg og etablering

Der er ikke identificeret relevante referencer med omtale af sikkerhedsforhold specifikt relateret til anlæg og etablering af CO_2-mellemlagre.

7.1.3 Drift

Almindelige farer ved drift af trykbærende udstyr i form af operationelle forhold der kan føre til farlige trykstigninger, er også gældende for CO_2-mellemlager.

Det antages at mellemlagre etableres på land. Der skal her være opmærksomhed på etablering af sikkerhedszoner omkring faciliteterne som følge af risikoen ved udslip af CO_2. I afsnit 5.1.1 er det vurderet, at der kan være afstande til en dødelighed på 1 – 5% på op til 300 meter for et stort momentant udslip og op til 200 meter for et kontinuert udslip fra en stor lækage. I Northern Lights projektet er der for mellemlageret udarbejdet konturer for stedbunden risiko, som indikerer at de gældende danske acceptkriterier kan overholdes, hvis der i en afstand på ca. 500 meter ikke placeres institutioner, der indgår i det offentlige beredskab eller findes institutioner med svært evakuerbare personer og i en afstand på ca. 200 meter ikke placeres boliger eller anden følsom anvendelse. Det vil være nødvendigt med lignende analyser for konkrete projekter.

I afsnit 5 er der en beskrivelse af de mulige farer og konsekvenser ved håndtering og udslip af CO_2.

Der er ikke fundet eksempler på uheld med CO_2-mellemlagre i de undersøgte referencer.

7.1.4 Afvikling

Ved afvikling (nedrivning) af CO_2-mellemlagre skal der udover de almindelige arbejdsmiljøregler være fokus på, at der ikke findes ansamlinger af stoffer og materialer i anlæggene, som kan udgøre en fare for medarbejderne i forbindelse med nedrivningsaktiviteterne. Umiddelbart er der ikke identificeret hjælpestoffer, som kan udgøre en fare ved nedrivning af mellemlagre. Undtagelse kan være ammoniak i køleanlæg.

Der er ikke fundet eksempler på uheld med CO_2-mellemlagre i de undersøgte referencer.

For mellemlagre vurderes der ikke at være fare for forurening af faciliteterne med farlige stoffer, som der skal tages hensyn til i forbindelse med nedrivningen.

7.2 Miljø

7.2.1 Forundersøgelser

Der er ikke fundet referencer der specifikt beskriver miljøforhold ved forundersøgelser for mellemlagre for CO_2.

De miljømæssige forhold ved forundersøgelser af mellemlagre vurderes at være sammenlignelige med hvad der findes i forbindelse med forundersøgelser for andre industrielle oplag af gas.

Det skal i forbindelse med planlægning sikres, at den valgte placering sker under hensyn til de risikomæssige og miljømæssige forhold. Det nødvendige plangrundlagt skal sikres og de nødvendige tilladelser være indhentet.

7.2.2 Anlæg og etablering

Der er kun fundet få referencer der specifikt beskriver miljøforhold ved anlæg og etablering af mellemlager for CO_2.

De miljømæssige påvirkninger under anlæg og etablering af mellemlager for CO_2 vurderes at være tilsvarende dem som identificeres for typiske øvrige industrielle lagre af gas og kemikalier.

Dette dækker følgende væsentligste påvirkninger der skal overvejes i de konkrete tilfælde: Støv og øvrige emissioner til luft knyttet til anlægsarbejde, brug af ressourcer, eventuel udledning af overfladevand eller vand fra grundvandssænkning, CO_2 aftryk i anlægsfase samt generering af støj.

I miljøkonsekvensrapporten for Northern Lights projektet nævnes at et tankanlæg med 12 tanke, hvor toppen af tankene vil nå op i ca. kote +45 har en stor visuel betydning i det åbne landskab og vil ændre landskabets karakter [40].

7.2.3 Drift

Der er kun identificeret få referencer der specifikt beskriver miljøforhold ved drift af mellemlager for CO_2.

De miljømæssige påvirkninger under drift af mellemlager for CO_2 vurderes at være meget tilsvarende dem som identificeres for typiske øvrige industrielle lagre af gas, olie og kemikalier.

Dette dækker følgende væsentligste påvirkninger der skal overvejes i de konkrete tilfælde: Støj fra pumper, kompressorer og andet industrielt udstyr, eventuelle diffuse emissioner af CO_2, brug af kemikalier til konditionering, korrosionsbeskyttelse mv. eventuelle udledninger via overfladevand og risiko for spild. Herudover eventuelle planlagte udledning af CO_2 og evt. N2 i forbindelse med vedligehold.

I miljøkonsekvensrapporten for Northern Lights projektet nævnes, at anlægget vil kunne efterleve støjkrav.

Endvidere nævnes at der ikke er planlagt udledning af CO_2 under normale driftsforhold. Kun i den unormale driftssituation, hvor anlægget ikke kan injicere gas i en længere periode, og der sker en trykforøgelse i anlægget, vil der kunne være behov for trykaflastning og udledning af CO_2 [17].

Herudover nævnes, at der ikke er risiko for forurening af overfladevand fra mellemlageret, idet der ikke vurderes at være kilder til en sådan forurening. Alt udstyr, som indeholder olie til køling, smøring, hydraulik mv. vil blive etableret således at eventuelle spild opsamles [17].

7.2.4 Afvikling

Der er ikke fundet referencer der specifikt beskriver miljøforhold ved afvikling af mellemlager for CO_2.

De miljømæssige forhold ved afvikling vurderes at være sammenlignelige med, hvad der findes i forbindelse med afvikling af andre industrielle anlæg.

Dette dækker følgende væsentligste påvirkninger der skal overvejes i de konkrete tilfælde: Affald i form af ikke genanvendelige anlægsdele, støj fra demontering og nedtagning, energiforbrug og emissioner fra transport og maskineri, eventuel udledning af CO_2 fra tømning af anlæg, eventuel brug af kemikalier til rensning af anlægsdele forud for nedtagning.

7.3 Natur

Naturpåvirkningen ved etablering af mellemlagerfaciliteter vil primært afhænge af anlæggets placering i forhold til den eksisterende natur. Arealbehov og anlægsfase vil medføre de samme naturpåvirkninger som ved etablering af andre anlæg, f.eks. inddragelse af beskyttede eller sårbare naturtyper og forstyrrelse af beskyttede arter som følge af fysiske indgreb, trafik og støj.

7.3.1 Forundersøgelser

Forud for etablering af mellemlagerfaciliteter vil der typisk blive foretaget feltundersøgelser (som for Northern Lights [41]) , som ikke i sig selv har en påvirkning på flora og fauna.

7.3.2 Anlæg og etablering

Øget trafik og støj fra anlægsarbejdet kan forstyrre fugle og pattedyr især i yngleperioden om foråret, hvor særligt større rovfuglearter er følsomme for forstyrrelse [41].

For Northern Lights CO_2-lager er det vurderet, at skibstrafikken i anlægsfasen til og fra selve anlægget ved Ljøsøyna vil forårsage mest støj for fisk, da anlægsarbejdet vil foregå over et par år. De fleste studier viser, at skader på fisk fra støjeksponering ikke fører til negative effekter på fiskebestande. [40]

7.3.3 Drift

For mellemlager facilitet for Northern Lights, placeret ved kysten ca. 30 km nordvest for Bergen, er det potentielle influensområde for naturpåvirkninger afgrænset til op til 500 meter fra anlægget [41].

For det konkrete projekt, er det vurderet, at arealbehovet har den største påvirkning i form af forringelse af naturområder med lokal landskabsøkologisk funktion [41] [40].

På grund af den konkrete placering, er der ikke en øget støjpåvirkning eller en væsentlig påvirkning af vigtige naturtyper eller rekreative aktiviteter i form af trekking- og vandreruter [41].

Uheld på mellemlagerfaciliteter er beskrevet i afsnit 7.1.3 og konsekvensen ved indånding af CO_2 er beskrevet i afsnit 5.1.1.

Påvirkningen på natur ved et uheld/udslip af CO_2, herunder kuldepåvirkning, er ikke vurderet i forbindelse med Northern Lights.

7.3.4 Afvikling

Naturpåvirkningen ved afvikling af mellemlagerfaciliteter er ikke vurderet specifikt for Northern Lights projektet. Det forventes dog, at naturpåvirkningen ved afvikling af mellemlagerfaciliteter generelt vil svare til påvirkningerne i anlægsfasen og er endvidere sammenligneligt med, hvad der findes for andre industrielle oplag af gas.

8 Geologisk lagring af CO_2 på land og til havs - Vurdering af sikkerhed, natur og miljø

8.1 Sikkerhed

8.1.1 Forundersøgelser

Ved forundersøgelser er der mulighed for, at man under boringer offshore rammer lommer af kulbrinter i form af olie eller gas, som kan resultere i et blowout. Blowouts af kulbrinter medfører risiko for brand og eksplosion, samt forurening af havmiljøet i tilfælde af udslip af olie. Sandsynligheden vurderes som lav, da der forud for boringerne er udført seismiske undersøgelser, som vil kunne give information om eventuel forekomst af olie og gas i undergrunden.

Der er rapporteret om blowouts fra boringer i naturlige forekomster af CO_2, f.eks. ved geotermi og ved udvinding af CO_2 fra naturlige kilder [15], se også afsnit 5.1.1. Mest prominent i Sheep Mountain, CO, USA i 1982, hvor det tog en uge at stoppe udslippet. Der er fra de nævnte uheld ikke blevet rapporteret om alvorlig skade på mennesker eller miljø.

CO_2 i undergrunden findes typisk i områder med vulkansk aktivitet og der er ikke kendskab til naturlige forekomster af CO_2 i den danske undergrund. Det vurderes med den danske geologi, således meget lidt at sandsynligt at ramme naturlige forekomster af CO_2 ved boringer i forbindelse med forundersøgelser.

Der er ikke fundet eksempler på uheld med større udslip i forbindelse med forundersøgelser for geologisk CO_2 lagring.

8.1.2 Anlæg og etablering

Som for forundersøgelser gælder det, at der er mulighed for blowouts ved boringer i forbindelse med etableringen, med de samme farer som nævnt for forundersøgelser.

Der er ikke fundet eksempler på uheld med større udslip i forbindelse med anlæg og etablering af geologisk CO_2 lagring.

8.1.3 Drift

Ved driften af et geologisk lager injiceres der CO_2 i et reservoir i undergrunden. Dette sker under tryk og hvis man mister kontrollen med processen eller får en stor lækage på udstyret, er der risiko for et stort udslip til omgivelserne.

Hvis den oplagrede CO_2 af en eller anden grund migrerer mod overfladen kan der ske forholdsvis store udslip af CO_2.

Der er i flere tilfælde rapporteret om dødsfald og skader på vegetationen ved udsivning fra naturlige forekomster af CO_2 [15]. I referencen nævnes f.eks.: Uheld ved Mammoth Mountain, CA, USA: én person er død, uheld ved Solfatara i Italien: skader på vegetation i et areal af 0,5 km², uheld i Albani Hills i Italien: død af husdyr, uheld ved Clear Lake, CA, USA: 4 personer døde, uheld ved Latera caldera, Italien: skader på vegetation og uheld i Dieng, Indonesien: 145 personer døde.

Der er ikke fundet eksempler på uheld specifikke for drift af geologiske CO_2 lagre i de undersøgte referencer, herunder store udsivninger på grund af migrering af den oplagrede CO_2.

De mulige konsekvenser af et stort momentant udslip af CO_2 er beskrevet i afsnit 5.

8.1.4 Afvikling

For lagre der er er velanalyserede, hvor der sker løbende monitorering og er placeret i områder, hvor den tektoniske aktivitet er lav, vurderes risikoen for store momentane udslip af CO_2 for værende meget lille.

Som nævnt i det forrige afsnit er der kendte eksempler på udsivning fra naturlige forekomster af CO_2 i undergrunden.

Der er ikke fundet eksempler på uheld specifikke for geologiske CO_2 lagre, hvor der ikke længere injiceres CO_2, i de undersøgte referencer, herunder store udsivninger på grund af migrering af den oplagrede CO_2.

De mulige konsekvenser af et stort momentant udslip af CO_2 er beskrevet i afsnit 5.

8.2 Miljø

8.2.1 Forundersøgelser

Offshore og kystnære geologiske lagre

Der er kun fundet én referencer der decideret forholder sig til den miljømæssige påvirkning ved forundersøgelser i forbindelse med geologisk lagring af CO_2.

Specifikke CCS projekt referencer angiver primært, hvilke tekniske metoder der har været anvendt i forundersøgelserne. Metoder som er tilsvarende dem som er beskrevet under 10A.3.1.

Metoderne vurderes endvidere at være meget tilsvarende dem som bruges i forbindelse med kortlægning og undersøgelse af lagre til olie og gas, hvorfor der kan hentes erfaring fra f.eks. miljøvurderingsrapporter for oliegas projekter.

I miljøkonsekvensrapport for Northern Lights projektet [40] er nævnt følgende miljømæssige påvirkninger fra forundersøgelserne:

- Udledninger til vand af kemikalier, boremudder, borespåner og cement mv. i forbindelse med boring og etablering af brønd.
- Støj og emissioner fra undersøgelsesskibe og borerig i forbindelse med hhv. undersøgelser, boring, transport og energiforbrug

I Northern Lights projektet forventes primært brug og udledning af kemikalier klassificeret jf. OSPAR klassificeringen[7] som "grønne" og kun enkelte gule i forbindelse med brøndboring og etablering.

Herudover nævnes et gennemsnitlig dieselforbrug for en borerig (West Hercules) til 44 ton per døgn, og at boringen har en estimeret varighed på 75 døgn inklusive brøndtest.

Tilsvarende miljømæssige påvirkninger ses i forbindelse med boring og seismiske undersøgelser udført i forbindelse med oliegasproduktion som f.eks. beskrevet i Redegørelse for miljømæssige og sociale virkninger ESIS-Tyra, september 2017 [42].

Energistyrelsen har udarbejdet en række standardvilkår for forundersøgelser til havs samt en vejledning vedrørende boring, som også må forventes at dække forundersøgelser og boringer i forbindelse med geologisk lagring [43] [44].

Onshore geologiske lagre

Typen af forundersøgelser på land vurderes ikke at være meget anderledes end dem som er beskrevet for offshore. Den store forskel vil være at forundersøgelserne sker med maskiner og udstyr på land. Det betyder, at de miljømæssige påvirkninger vil ske på land i mindre afstand til mennesker, beboelse og naturarealer på land. Affald og spild vurderes at udgøre en mindre miljømæssig påvirkning idet der på land kan ske en kontrolleret opsamling og håndtering.

8.2.2 Anlæg og etablering

Offshore og kystnære geologiske lagre

Der er kun identificeret få referencer der decideret forholder sig til den miljømæssige påvirkning ved anlæg og etablering af et geologisk lager af CO_2.

[7] Kemikalier klassificeres jf. OSPAR i grupperne: PLONOR (grønne), Ranking (gule), Substitution (røde). Typisk gives tilladelse til anvendelse af grønne og gule kemikalier hvorimod røde kun kan avendes efter en særskilt tilladelse fra Miljøstyrelsen. Sorte kemikalier er de mest skadelige for havmiljøet, og en udskiftning har højt prioriteret. De er optaget på en særlig liste over miljøskadelige stoffer.

I anlægs- og etableringsfasen skal der bores en brønd til injektion af CO_2 og de permanente installationer til injektion på land hhv. på offshore installation skal etableres.

I miljøkonsekvensrapport for Northern Lights projektet [40] er nævnt følgende miljømæssige påvirkninger fra anlæg og etablering:

- Udledninger til vand af kemikalier, boremudder, borespåner og cement mv. i forbindelse med boring og etablering af brønd. Herudover nævnes anvendelse af mindre mængde radioaktiv materiale samt udledning af formationsvand i forbindelse med brøndtest.

- Støj og emissioner fra supportskibe og borerig i forbindelse med hhv. transport og energiforbrug

Tilsvarende miljømæssige påvirkninger ses i forbindelse med boring og seismiske undersøgelser udført i forbindelse med oliegasproduktion beskrevet i f.eks.: Redegørelse for miljømæssige og sociale virkninger ESIS-Tyra, september 2017 [42].

Onshore geologiske lagre

Anlæg og etablering af geologisk lager på land vurderes ikke at være meget anderledes end som er beskrevet for et offshore lager. Den store forskel er at anlæg og etablering sker på land med landgående maskiner og transportmetoder. Det betyder, at der i langt højere grad vil være risiko for påvirkning af mennesker i umiddelbar nærhed af site. Samtidig vurderes f.eks. affald og spild at udgøre en mindre miljømæssig påvirkning idet der på land kan ske en kontrolleret opsamling og håndtering.

8.2.3 Drift

Drift af geologisk lager indbefatter injektion af CO_2 i lageret, vedligehold af brønd samt monitorering af lageret.

Offshore og kystnære geologiske lagre

De miljømæssige påvirkninger nævnt for Northern Lights projektet inkluderer [40]:

- Anvendelse og udledning af nitrogen til spuling og test af anlægget.

- Risiko for ventilering af et overskudsvolumen af CO_2 ved opstart og ventilering.

- Udledning af hydraulikvæske fra åbning af fjernstyrede ventiler på subsea-installationer. Der estimeres en udledning på ca. 2.000 liter pr brønd pr år. Udledningen forventes at være højere i starten på grund af hyppigere test.

- Mulig udledning af kemikalier i forbindelse med brøndtest

- Mindre diffuse udledninger af CO_2 fra tryksatte koblinger, flanger og ventiler
- Øget energiforbrug inkl. tilhørende emissioner til drift af ventiler mv. ved brønden

Det estimeres at drift af modtageanlæg og permanent geologisk CO_2 lager vil medføre en CO_2 udledning på 0,1 % af modtage kapaciteten for lageret [40].

Monitorering udført fra 1996 og frem til 2017 af CO_2 udledning fra Sleipner viser, at der ikke sker udledning af CO_2 [45]. Konklusionen fra den løbende monitorering af dette projekt er blandt andet at CO_2 forbliver sikkert i lageret og at seismiske undersøgelser er vigtige i monitorering af lageret både i forhold til udslip og i forhold til CO_2'ens opførsel i lageret [45].

Onshore geologiske lagre

Drift af et onshore lager for CO_2 vurderes ikke at have væsentlige anderledes miljømæssig påvirkning end et offshore lager for CO_2. Herudover kan et onshore lager for CO_2 sammenlignes med onshore lager for naturgas f.eks. Stenlille.

I miljøvurdering hhv. miljøgodkendelse for Stenlille gaslager [46] [47] nævnes følgende miljømæssige påvirkninger:

- Røggasemissioner fra kedler og nødgeneratorer ved test og eventuelle strømudfald.
- Risiko for udslip af gas ved trykaflastning af udstyr
- Støj fra ventiler, kompressorer og andet udstyr
- Risiko for lækage af gas til grundvandsmagasin eller øvre jordlag
- Risiko for lækage af forurenende stoffer fra f.eks. olietank og fra lager og håndtering af formationsvand

Det anføres at drift og indretningen af lageret skal tilrettelægges på en sådan måde, at muligheden for grundvandsforurening i praksis kan udelukkes. Det er endvidere vurderet at mulighederne for at monitere et eventuelt gasudslip, førend det kan medføre nogen skade i området, er særdeles gunstige ved Stenlille.

I dokumentationen fra pilotanlægget i Lacq, Frankrig anføres det, at der ikke er detekteret tilfælde af CO_2 lækage og at der ikke har være påvirkning af økosystemet [48]. Miljøvurdering fra samme projekt konkluderer endvidere, at der ikke er påvist væsentlige miljøpåvirkninger [35] af projektet.

Også data fra Illinois Basin, Decatur projektet viser at CO_2 bliver i det geologiske lager. Det anføres at der ikke er identificeret CO_2 lækager eller andre væsentlige påvirkninger [49].

Ovenstående erfaringer fra de enkelte CO_2 lagre underbygges af en opsummerende artikel fra The Electricity Journal. Her anfører at de seneste 50 års erfaring med geologisk lagring af CO_2 viser at sandsynligheden for større udsivning af CO_2 er meget lav [50].

8.2.4 Afvikling og monitorering

Afvikling af en geologisk lagring for CO_2 vil bestå af brøndlukning – eventuel decomissionering af installationer og rør. Herudover vil fortsat ske monitorering af lageret.

I Northern Lights projektet anføres det, at ved afslutning af injektion og lukning af lageret vil brønde lukkes og anlæg på havet vil blive fjernet jf. OSPAR-beslutning 98/3. Rørledninger og kabler vil blive håndteret jf. gældende retningslinjer på lukningstidspunkt. Det anføres, at det forventes at rør og kabler efterlades såfremt de ikke udgør en risiko for bundfiskeri [40].

Det er endvidere for det projekt aftalt, at der forud for lukning skal udarbejdes en afviklingsplan, som i detalje beskriver lukning og nedtagning af anlægsdele, samt hvordan overvågning af lageret tænkes udført efter afslutning af injektion.

Miljøforhold ved monitorering af det geologiske lager efter lukning vil svarer til dem som er beskrevet under forundersøgelser.

Miljøforhold ved lukning og afvikling af permanente installationer inkl. rørledninger vurderes endvidere at være de samme, som ses ved tilsvarende anlæg anvendt til udvinding af olie og gas. Dog med den væsentlige fordel at anlæg og anlægsdele ikke er forurenet med kulbrinter, og at der efter afvikling/lukning skal fortsættes med løbende monitorering af det geologiske lager.

8.3 Natur

8.3.1 Forundersøgelser

Som en del af de indledende forundersøgelser gennemføres seismiske undersøgelser, som kan påvirke natur og levende organismer både på land og på vand.

Seismiske undersøgelser på land

Ved seismiske undersøgelser på land i Danmark, afhænger påvirkningen på naturen af, hvilket materiel og køretøjer, som anvendes og om undersøgelsen foretages fra veje eller ubebyggede arealer. Vilkårene for undersøgelsen reguleres gennem tilladelser til de enkelte forundersøgelser.

For seismiske undersøgelser på land i Grønland, er det i en rapport fra 2020 vurderet, at påvirkninger på naturen afhænger af, hvilke metoder der anvendes og hvornår på året undersøgelserne udføres. Der anvendes meget store og tunge køretøjer, der sætter store aftryk i landskabet ved at beskadige vegetation og det organiske lag, hvorved permafrost og vandafstrømningsforhold ændres. Der er også ofte tale om kraftige forstyrrelser af fugle- og dyrevildt. [51]

Af afværgeforanstaltninger, som kan være relevante for andre områder end de arktiske, nævnes i undersøgelsen:

- Forhindre nedsivning af brændstof og andre skadelige stoffer, f.eks. ved placering af spildbakker, som vil kunne opsamle miljøfarlige væsker.
- Planlægge hvornår og hvor, der køres med tunge køretøjer, for at forhindre skade på vegetation og sårbare områder.
- Mindske forstyrrelse af fugle- og dyrevildt, ved at undgå sårbare perioder og områder som er udpeget som vigtige habitater for dyrevildt. [51]

I Danmark vil de samme typer af afværgeforanstaltninger være relevante at overveje, især inden for arealer med naturbeskyttelse eller i områder, hvor der findes beskyttede arter, som er sårbare overfor fysisk påvirkning og forstyrrelser.

Marine seismiske undersøgelser

Ved seismiske undersøgelser til søs inden for dansk territorium, afhænger påvirkningen på naturen af, hvilke fartøjer og metoder, som anvendes og i hvilket konkret område undersøgelsen foretages. Vilkårene for undersøgelsen reguleres gennem tilladelser til de enkelte forundersøgelser.

Seismiske undersøgelser på havet kan påvirke fisk og marine pattedyr [52] [53] [40] [42]. Niveauet af påvirkningen fra undervandsstøj kan overordnet opdeles i:

- Hørbart niveau, som afhænger af arter
- Maskering af øvrige lyde, f.eks. kommunikation
- Påvirkning af adfærd, f.eks. fødesøgning
- Fysiske skader på høreorganerne, i form af hørenedsættelse eller høretab.

Den konkrete påvirkningen vil afhænge af, hvilke arter der udsættes for undervandsstøj. Der er potentielt en direkte påvirkning af det enkelte individ i form af høreskader eller -tab og en indirekte påvirkning af bestande, hvis fødesøgning og navigation forstyrres. I miljøvurdering af Tyra, henvises der til et studie af marsvin under en 2D-seismisk undersøgelse i Moray Firth, hvor det blev konstateret, at dyr udviste kortvarig undvigeadfærd inden for 5-10 km omkring området for seismisk dataindsamling. Samlet set kan risikoen for virkninger på havpattedyr være lokal (hørenedsættelse) eller regional (adfærdsmæssig). [42]

I forbindelse med Northern Lights, er der gennemført grundige miljøvurderinger af påvirkningen ved at gennemføre marine seismiske undersøgelser. Northern

Lights CO_2-lager er placeret i den norske del af Nordsøen og forholdene er derfor sammenlignelige med danske forhold, selvom der er specifikke arter og naturtyper, som ikke findes inden for den danske del af Nordsøen.

Dyrelivet i havet vurderes at påvirkes kraftigere af støj og på større afstande end arter på land ved f.eks. seismiske undersøgelser, da lyd propagerer hurtigere og længere i vand end i atmosfærisk luft [3].

Seismiske luftkanoner kan påvirke fisks adfærd i området tæt på det seismiske fartøj. I redegørelse for miljømæssige virkninger af opgradering af eksisterende anlæg på Tyra-feltet, forventes det dog, at seismiske undersøgelser generelt ikke vil føre til langvarige ændringer i fiskebestandenes størrelser og at virkningen vurderes at være af lille intensitet, af lokalt omfang og af kort varighed [42].[8]

For hørenedsættelse og adfærdsmæssige virkninger på marine pattedyr vurderes påvirkningen at være af lille intensitet, da sandsynligheden for, at undersøgelsesfartøjer støder på havpattedyr og andre havarter i et område med risiko for virkning, er lille. Det vurderes, at populationerne af havpattedyr i Nordsøen ikke vil blive påvirket af seismiske aktiviteter ved TYRA-projektet. Virkningen vurderes at være af lille intensitet, af lokalt eller regionalt omfang og mellemlangvarige eller langvarige. Den overordnede virkning på havpattedyr af undervandsstøj fra seismiske undersøgelser vurderes at være af moderat negativ overordnet betydning. [42]

For Northern Lights CO_2 lager, vil der før opstart af injektion blive gennemført en baseline seismisk undersøgelse, som danner et sammenligningsgrundlag for den senere overvågning af CO_2. Området som dækkes vil være i størrelsesorden 550 km^2, og undersøgelsen varer ca. to måneder og kan påvirke yngel og larver af fisk, hvis undersøgelsen gennemføres i gydeperioden og umiddelbart efter [40].

I Northern Lights projektet er det anført, at der gennem driftsperioden vil gennemføres seismiske undersøgelser af det geologiske lager i en størrelsesorden 200 km^2. Her er det ligeledes anført at de seismiske undersøgelser kan give skade på fisk og pattedyr. Det anføres, at påvirkningen er afhængig af metoden der anvendes. En "soft start" angives som mulig afværgeforanstaltning således at lydfølsomme fisk og pattedyr skræmmes bort. Det anføres at seismiske undersøgelser med års mellemrum vil have midlertidige effekter på fiskebestande i det berørte områder. [40]

For Northern Lights CO_2 lager er det vurderet, at omfanget af direkte skade på dyrenes hørelse er begrænset til nærområdet nogle hundrede meter fra kilden, og at der ikke vil være en påvirkning på populationsniveau. Marsvin, spækhugger og vågehval undviger ved lavere støjniveauer end mange andre arter, og det

---

[8] I VVM-redegørelse for Tyra, henvises til følgende kilde:
Norwegian Oil Industry Association (OLF). 2003. Seismic surveys impact on fish and fisheries by Ingebret Gausland.

kan derfor ikke udelukkes, at seismiske undersøgelser kan påvirke de marine pattedyr i området, hvor de seismiske undersøgelser gennemføres. Påvirkningen er vurderet til noget forringet[9] [40].

Undervandsstøj er en form for energi, der i ekstreme tilfælde kan påvirke plankton, f.eks. på grund af nedbrydning af celler (cellelyse). Undervandsstøj som beskrevet for Tyra-projektet, som omfatter olie-/gasindvinding i Nordsøen, kan genereres fra seismiske aktiviteter (luftkanoner, multibeam-ekkolod og sidesøgende sonar), spunsramning under konstruktion af nye platforme, ramning af konduktorer, boring, afvikling og forskellige fartøjer. På grundlag af planktonpopulationernes meget tætte bestandtæthed og deres høje reproduktion forventes plankton at genoprette sig selv efter forstyrrelsen [42].

Skadelige påvirkninger af fisk og pattedyr som følge af seismiske undersøgelser og overvågning, medfører en lokal, midlertidig påvirkning, hvor det er muligt at undgå skadelige påvirkninger med afværgeforanstaltninger [52], f.eks. afværgetiltag som "soft-start" og brug af fiskerikyndigt mandskab ombord [40].

Af miljøvurderingen af Tyra-projektet, fremgår det, at risikoen for, at undervandsstøj påvirker havpattedyr i forbindelse med geofysiske aktiviteter og anlægsprojekter, generelt afværges ved hjælp af følgende tiltag:

- På steder, hvor det må forventes, at der vil ske en påvirkning af havpattedyr, vurderes den bedste tilgængelige teknologi.
- Planlægning og effektiv udførelse af geofysisk dataindsamling og anlægsprojekter, så den samlede varighed af arbejdet forkortes, og følsomme arters eksponering for støj minimeres.
- Overvågning af havpattedyrenes tilstedeværelse inden iværksættelse af støjende aktiviteter og i forbindelse med geofysisk dataindsamling eller anlægsarbejde.
- Der etableres en eksklusionszone, hvor arbejdet bliver udsat, hvis der viser sig at være havpattedyr til stede inden arbejdets påbegyndelse.
- Procedurer til "soft" opstart, også kaldet ramp-up, skal benyttes i de områder, hvor der er påvist aktivitet af havpattedyr. Det betyder, at lydsignalniveauet gradvist forøges til fuldt operationelt niveau, så dyret har mulighed for at fjerne sig fra de generende lyde. Derved reduceres risikoen for eventuelle påvirkninger fra den genererede undervandsstøj. [42]

I Danmark vil de samme typer af afværgeforanstaltninger være relevante at overveje, især inden for arealer med naturbeskyttelse eller i områder, hvor der findes beskyttede arter, som er sårbare over for støj og forstyrrelser. Afværge-

[9] Efter vurderingsmetode i miljøvurdering af Northern Lights.

foranstaltninger vil blive fastlagt efter en konkret vurdering af et projekts påvirkning og vil typisk omfatte foranstaltninger, som reducerer eller undgår væsentlige, negative påvirkninger.

Visse foranstaltninger for at mindske eller undgå en påvirkning af marine pattedyr og fisk er allerede standardprocedure i Danmark og/eller en del af de tilladelser, som gives [43]. Der kan være identificerede påvirkninger, som forstyrrelse af marine pattedyr i et større område, som ikke afværges med de foranstaltninger, som typisk anvendes.

8.3.2 Anlæg og etablering til havs

Under anlæg og etablering kan der være behov for seismiske undersøgelser – se påvirkning på natur under forundersøgelser i afsnit 8.3.1.

I anlægsfasen til havs kan marine pattedyr og fisk potentielt påvirkes af anlæg af installationer [53], herunder støj fra skibstrafik, øget turbiditet[10] og risiko for spredning af sedimenter, næringssalte og miljøgifte/kemikaliesammensætning [40] [42].

Arealbehov

Afhængigt af det konkrete projekts placering og arealbehov, kan der være en permanent påvirkning af natur- og miljøbeskyttelsesområder [3], herunder Natura 2000-områder [54] [53], vigtige marine naturtyper samt gydeområder [40].

I forbindelse med arealbehovet, kan der være et tab af områder for fisk der gyder på bunden (tobis) og reduceret fiskeri omkring anlæg og ikke nedgravede rørledninger pga. fiskerifri zoner og sikkerhedszoner [53].

Havbund

Ved etablering og placering af anlæg, brønde og rørledninger, vil der være en påvirkning af havbunden [3] [42], herunder permanent ødelæggelse af havbund/habitater og midlertidig påvirkning som følge af sedimentspredning [52] samt ændring af havbunden ved akkumulering af bore-mudder [53]. Boring af brønde medfører ophobning af materiale med kemikalier bundet til sedimentet. Sedimentet spredes hurtigt af vandstrømmen, men der er observeret lokale effekter i overvågningsprogrammer [52].

Fysisk forstyrrelse på havbunden kan forekomme under "site undersøgelser", 4D-seismiske undersøgelser, boring, installation af platforme og rørledninger samt afvikling. De fysiske forstyrrelser fra disse aktiviteter forventes ikke at forekomme samtidig. [42]

---

[10] Turbiditet anvendes om vandets klarhed/renhed og er et mål for suspenderet stof i vandet, f.eks. fine partikler som mineraler, organiske stoffer og bakterier.

For Northern Lights CO_2 lager forventes en lille spredning af partikler og dermed miljøgifte i forbindelse med etablering af rørledningen og kun begrænset ophvirvling som følge af udlæg af sten langs rørledningen. Der forventes ingen påvirkning på bundfaunaen som følge af sedimentspredning [40]. For projektet er det desuden vurderet, at der vil ske en ændring af habitater, hvor der udlægges sten langs rørledningen. Da det konkrete område ikke rummer sjældne arter eller unik bundfauna og der samtidig er tale om et begrænset areal, er den samlede påvirkning af bundfauna vurderet til ubetydelig [40].

I miljøvurdering af Tyra, er det vurderet, at den mest intense virkning på havbunden forårsages af tracering, hvor nye rørledninger nedgraves til en dybde på ca. 1.5-2 m under havbundsoverfladen. Tracering af rørledningen i havbunden foregår ved hjælp af pløjning, nedspuling eller mekanisk skæring. Under denne proces suspenderes havbundssediment ind i vandsøjlen. Baseret på erfaringer fra andre rørledningsprojekter[11] vurderes det, at det suspenderede sediment bundfældes inden for nogle få hundrede meter fra det forstyrrede område [42].

Støj og lys

Støjpåvirkning i forbindelse med seismiske undersøgelser/monitorering er behandlet i afsnit 8.3.1.

For Northern Lights CO_2 lager vil installation af rørledning og kabler, samt etablering af stenfyld i rørledningstracéet medføre støj. Det er vurderet, at der ikke er nogen negativ påvirkning af marine pattedyr fordi arbejdet vil flytte sig og foregå over en begrænset periode, hvor dyrene vil have mulighed for at trække væk fra området under anlægsarbejdet. For den konkrete lokalitet, er der allerede en høj grad af skibstrafik i området, og det forventes derfor ikke at skibstrafik i anlægsfasen vil påvirke marine pattedyr i nævneværdig grad. [40]

I det omfang, der anvendes belysning på fartøjer og faste installationer over vandet, kan det have en påvirkning på arter over og under vandet [52]. Fugles navigation kan blive forstyrret og de tiltrækkes især af lys på offshore olie-gasplatforme, hvor belysningen har en effekt på store afstande [55]. I forbindelse med Tyra, er det vurderet, at den potentielle forstyrrelse af fisk fra lys på rigge,

---

[11] I VVM-redegørelsen for Tyra henvises til følgende kilder:

Neff, J.M., Anderson, J.W. 1981. Response of marine animals to petroleum and specific petroleum hydrocarbons. Halsted Press. New York.

Nord Stream. 2009. Environmental Impact Assessment: Documentation for Consultation under the Espoo Convention Nord Stream Espoo Report: Key Issue Paper Seabed Intervention: Works and Anchor Handling.

Todd VLG, Todd IB, Gardiner JC, Morris ECN, MacPherson NA, DiMarzio NA, Thomsen F, 2015. Review of impacts of marine dredging activities on marine mammals. ICES Journal of Marine Science 72, 328–340.

platforme og fartøjer forventes at være lokal og sprede sig 90-100 m fra kilden [42].

Vandkvalitet

Boring af brønd vil medføre støj og øget turbiditet i vandmasserne, som kan føre til at marine pattedyr undviger området. For Northern Lights CO_2 lager forventes det ikke at marine pattedyr bliver påvirket af boringen i nævneværdig grad [40].

Fisk påvirkes under anlægsarbejdet af øget turbiditet i vandsøjlen, som vil kunne medføre dårligere sigt under fødesøgning og potentiel undvigelse af området [40]. Havfugle kan ligeledes påvirkes af øget turbiditet, som kan gøre fødesøgningen mere udfordrende for fuglene, hvis anlægsarbejdet gennemføres i sårbare perioder som yngleperioden [40].

Fisk er følsomme over for lydtryk og partikelbevægelse. Voksne fisk er meget mobile og kan svømme væk fra områder, som er forstyrrende, i modsætning til larver og yngel som er mindre mobile. Rørlægningsarbejdet flytter sig langs tracéet med ca. 4 km i døgnet, dvs. at støj og forstyrrelser i forbindelse med arbejdet dermed vil foregå i en meget begrænset periode i det enkelte område [40].

I miljøvurdering af Tyra, er det vurderet, at virkningen på vandkvalitet, som følge af suspenderet materiale ved anlæg af rørledningen, vurderes at være af lille intensitet, af lokalt omfang og af kort varighed. [42]

Udledning af vandbaseret boremudder og vandbaserede borespåner under de planlagte boreaktiviteter kan påvirke vand- og sedimentkvaliteten omkring boreriggen.

Når vandbaseret mudder og vandbaserede spåner, der er slam af partikler af forskellige størrelser og tætheder i vand, der indeholder opløste salte og organiske kemikalier, udledes til havet, dannes der en fane, som hurtigt fortyndes, da den driver væk fra udledningsstedet med de dominerende vandstrømme. Feltundersøgelser af koncentrationen af suspenderede stoffer i faner af boremudder og -spåner i forskellige afstande fra boreaktiviteten har bekræftet dette mønster, og det kan konkluderes, at koncentrationen af suspenderede borespåner og -mudder falder meget hurtigt på grund af materialets sedimentation og fortynding [56] [57].

Kemikalier og næringsstoffer

Udslip af kemikaliebehandlet vand ved brønden fra klargøringen af rørledningen før drift, er for Northern Lights planlagt gennemført i juli og august måned. Makrel gyder i perioden maj-juli, mens nordsøsild gyder i perioden august–februar. Begge arter har gydeområder langt fra brøndområdet, og det vurderes at udslip af kemikalieholdigt vand hurtigt vil fortyndes og vil medføre ubetydelig påvirkning på drivende æg og yngel. [40]

For Northern Lights CO_2-lager er det vurderet, at rørlægning og udlægning af sten kan give en lokal spredning af mindre mængder partikler og næringsstoffer nær havbunden, samt eventuelle miljøgifte i sedimenterne i Hjeltefjorden. Dette vil relativt hurtigt sedimentere igen. [40]

Udledningerne af vand, olie og kemikalier indeholder stoffer, der kan fungere som næringsstoffer for fytoplankton og bakterier i vandet [42].

Plankton

For Northern Lights CO_2 lager forventes ingen påvirkning på plankton ved etablering af rørledning, da arbejdet medfører meget begrænset resuspension[12] af sediment og kun på dybt vand. Der kan være miljøfarlige stoffer i det sendiment, som ophvirvles fra havbunden, men det forventes ikke, at det vil være i så høje koncentrationer, at det har en negativ påvirkning af det marine miljø. Det vurderes, at der er en ubetydelig påvirkning, som er kortvarig, hurtigt reversibelt og kun påvirker et meget begrænset område. [40]

Forskellige aktiviteter ved Tyra-projektet forventes at medføre sedimentresuspension, og det kan føre til øget vandturbiditet og tilførsel af næringsstoffer (primært ammonium og fosfat), der kan stimulere bakterie- og fytoplanktonvækst i vandet [42].

8.3.3 Drift

Under drift og injektion kan der være behov for seismiske undersøgelser/monitorering – se påvirkning på natur under forundersøgelser i afsnit 8.3.1.

Offshore og kystnære geologiske lagre

Et EU-forskningsprojekt fra 2011-2015, ECO2, opsummerede påvirkninger på marin natur ved CO_2-lagring ved de aktive lagre, Sleipner og Snøhvit, samt et kommende lager i Polen. Studiet undersøgte konsekvenser af CO_2-udslip ved laboratorieforsøg, et kontrolleret forsøgsudslip ved Sleipner og undersøgelse af lokaliteter med naturlig CO_2-udsivning. Forskningsprojektet konkluderer, at CO_2 gasbobler opløses inden for et par meter, og at forsuring/fald i pH-værdi forsvinder inden for 1 km. Studiet refererer til forsøg, som har vist, at fisk og skaldyr kan blive påvirket ved konstante udledninger og lav pH-værdi, som over tid kan opløse kalkskaller og muslinger. De miljømæssige påvirkninger af udslip vurderes samlet set som små, også ved potentielle udslip fra flere CO_2-lagre. [58]

I forbindelse med fysiske anlæg på havbunden, som ikke-nedgravede rørledninger, kan der opstå revlignende effekter [53]. Ved udlægning af sten langs rørledningen og ved krydsninger, vil habitater i området ændres. For Northern Lights er der tale om et område på 5.500 m^2, hvor det dog vurderes, at bundfaunaen i området ikke er unik for området og at arterne findes flere steder langs kysten. Områderne som dækkes til af sten er begrænsede. Der forventes

---

[12] Opblanding af partikler/sediment i vandet, som f.eks. ophvirvles ved forstyrrelse af havbunden under anlægsarbejde.

ingen påvirkning på ansvarsarterne eller at biodiversiteten i området vil reduceres. Påvirkningen vurderes derfor som ubetydelig, med *ingen konsekvenser*[13] for bundfauna. [40]

Rørledninger kan få vandet til at strømme hurtigere foran rørledningen og dermed erodere havbunden og/eller skabe aflejringer bag den. Vandbevægelsen kan også bevirke, at bunden under rørledningen eroderer. Rørledninger med tilknytning til Tyra-projektet nedgraves ved tracering eller dækkes med sten, hvilket minimerer erosionsvirkningerne. [42]

Med hensyn til svampeorganismer, der lever på faste undervandskonstruktioner, vil disse fungere som filtre for den plankton, der findes i de gennemstrømmende vandmasser. Dette vil ændre den lokale fødekæde og dermed den lokale biologiske produktion og nedbrydning af organisk stof i området. Selv om dette vil påvirke økologien i et område, der er flere gange større end det område, der optages af felterne, er det stadig en mindre påvirkning af det regionale økosystem. [42]

I miljøvurdering af Danmarks havplan, er det vurderet for de to udlagte områder til CO_2-lagring i Nordsøen, at der vil der være en forstyrrelse af kyst- og havfugle på grund af skibstrafik i løbet af driftsfasen [53].

I forbindelse med EU's CO_2-lagringsdirektiv, er det vurderet, at der i tilfælde af meget usandsynlige mindre CO_2-lækager, kun vil være lille lokal marin påvirkning. Dette skyldes, at de marine økosystemer er robuste over for mindre udsving i CO_2 koncentration. Selv ekstremt usandsynlige større lækager vil have en begrænset og midlertidig effekt på marine økosystemer [59].

Den lille risiko for lokale marine økosystemer, som følge af CO_2-lagring, skal opvejes med de omfattende påvirkninger, som klimaforandringer og relateret forsuring af havene medfører i dag [59].

I forbindelse med eventuel lækage fra Northern Lights CO_2 lager, er det vurderet, at der vil være en ubetydelig påvirkning af det marine miljø. Dette er begrundet i typen af uheld, hvor der er tale om et akut udslip med begrænset spredningsområde og at CO_2 forventes at blive fortyndet hurtigt i vandmasserne [40].

Onshore geologiske lagre

I driftsfasen for geologisk lagring på land, vil der være behov for at overvåge lageret og de eventuelle påvirkninger på jord, luft, flora og fauna samt grundvand og overfladevand. Overvågningen kan have samme påvirkninger på naturen, som for de indledende forundersøgelser i form af seismiske undersøgelser, besigtigelser og opsætning af måleudstyr.

---

[13] Jf. vurderingsmetode i miljøvurdering af Northern Lights projektet.

For lagringsområdet ved Lacq har der været gennemført et overvågningsprogram gennem 5 år, baseret på et baseline studie i 2009. Overvågningen bestod blandt andet af forskellige målestationer og regelmæssige registreringer. For påvirkningen på flora og fauna er der påvist mindre fluktuationer over årene, som kan tilskrives øvrige påvirkninger end CO_2-lageret. Det er dog samtidig vurderet, at de 5 år er for kort en overvågningsperiode til at afskrive påvirkninger fra CO_2-lageret [35].

CO_2 anses ikke i sig selv som forurenende i vand, men ved opløsning danner CO_2 en svag syre, kulsure, som kan medføre udvaskning af andre forurenende metaller eller mineraler, som arsenik, bly og organiske forbindelser, som kan forurene grundvand og drikkevand. [60]

8.3.4 Afvikling

Under afvikling kan der være behov for seismiske undersøgelser/monitorering – se påvirkning på natur under forundersøgelser i afsnit 8.3.1.

9 Transport af CO_2 på land og til havs - Vurdering af sikkerhed, natur og miljø

9.1 Sikkerhed

9.1.1 Forundersøgelser

Der er ikke identificeret relevante referencer med omtale af sikkerhedsforhold specifikt relateret til forundersøgelser for etablering af transport infrastruktur for CO_2.

9.1.2 Anlæg og etablering

Hvad angår transport med lastvogn, tog eller skib antages det, at der vælges eksisterende standardmateriel, som er indrettet i henhold til de internationale transportregler for CO_2 (ADR, RID og IMDG). Derfor ingen specifikke forhold for transport af CO_2.

Ved lægning af rørledninger er der en række fysiske farer (håndtering af tungt udstyr, klemfare, druknefare og lign.), både til havs og på land, som ikke er relateret specifikt til anlæg af CO_2-rørledninger. I anlægsfasen er der ikke CO_2 i rørledningerne og derfor ingen fare for udslip af CO_2.

9.1.3 Drift

Ved transport med lastvogn, tog eller skib gælder de internationale transportregler for CO_2 i henhold til ADR, RID og IMDG.

I estimaterne nævnt i afsnit 5.1.1 er der udregnet konsekvensafstande på ca. 30 meter til 1 – 5% dødelighed, for momentane udslip på 50 tons CO_2, hvilket antages at repræsentere et udslip fra en lastvogn eller en togvogn. For skibstanke, som må formodes at være større, kan konsekvensafstanden være op til 300 meter.

Almindelige forholdsregler for drift af trykbærende rørledninger er også gældende for drift af rørledninger med CO_2.

I estimaterne nævnt i afsnit 5.1.1 er der udregnet konsekvensafstande[14] på ca. 200 meter, for et stort kontinuert udslip, som antages at repræsentere et stort udslip fra en rørledning. Et fuldstændigt rørbrud vil give større konsekvensafstande, men vi har ikke kendskab til modellering af sådanne udslip. Det må antages at konsekvensafstanden i sådan et tilfælde er mindst 300 meter, svarende til et momentant udslip på 2.000 tons. De nævnte konsekvensafstande gælder

[14] Konsekvensafstanden er defineret som den afstand, inden for hvilken, der er en risiko for død på 1-5%

for udslip til atmosfæren. Ved udslip til havs vil den undslupne CO_2 fortyndes/optages i vandsøjlen, når den stiger op til overfladen, så den ikke udgør en fare for mennesker.

I afsnit 5 er der en beskrivelse af de mulige farer og konsekvenser ved håndtering og udslip af CO_2.

Der er fundet forskellige artikler i aviser og tidsskrifter om et uheld med udslip fra en rørledning i USA i februar 2020. Der foreligger endnu ikke resultater af officielle undersøgelser af uheldet. Ud fra hvad der kan udledes af artiklerne, er der tale om et totalt rørbrud på en nedgravet rørledning som følge af forskydninger i jorden efter heftige regnskyl. Gasskyen var angiveligt grønlig og stærkt stinkende, hvilket indikerer at der ikke var tale om ren CO_2. Angiveligt var der også H_2S i rørledningen. Ingen mennesker kom alvorligt til skade [61].
Der er ikke fundet eksempler på uheld med CO_2-transport i de undersøgte referencer.

9.1.4 Afvikling

Ved demontering af rørledninger skal der udover de almindelige arbejdsmiljøregler være fokus på, at der ikke findes ansamlinger af stoffer og materialer i rørledningerne, som kan udgøre en fare for medarbejderne i forbindelse med demonteringen. Umiddelbart er der ikke identificeret hjælpestoffer, som kan udgøre en fare ved nedrivning af rørstrækninger.

Skrotning af lastvogne, togvogne og skibe til transport af CO_2 vurderes ikke at være relevant i denne sammenhæng.

Der er ikke fundet eksempler på uheld ved demontering af rørledninger i de undersøgte referencer.

9.2 Miljø

9.2.1 Forundersøgelser

Rørledninger, Lastbil, godstog, skib

Der er ikke fundet referencer, der specifikt beskriver miljøforhold ved forundersøgelser for infrastruktur til transport af CO_2.

De miljø- og naturmæssige forhold ved forundersøgelser for infrastruktur til transport af CO_2 vurderes at være sammenlignelige med hvad der findes i forbindelse med forundersøgelser for infrastruktur til transport af naturgas, LPG, LNG og andre industrielle gasser.

Det skal i forbindelse med planlægning sikres, at det valgte tracé hhv. transportruter sker under hensyn til de risikomæssige og natur- og miljømæssige forhold.

Det nødvendige plangrundlag skal sikres for rørledninger, og de nødvendige tilladelser være indhentet.

9.2.2 Anlæg og etablering

Rørledning

Der er kun identificeret få referencer der specifikt beskriver miljøforhold ved anlæg og etablering af rør til transport af CO_2.

De miljømæssige påvirkninger under anlæg og etablering af ny rørledning for CO_2 vurderes at være tilsvarende dem, som identificeres for typiske øvrige rørledninger anvendt til f.eks. transmission og distribution af naturgas.

Dette dækker følgende væsentligste miljøpåvirkninger der skal overvejes i de konkrete tilfælde: Støv og øvrige emissioner til luft knyttet til anlægsarbejdet, brug af ressourcer, eventuel udledning af overfladevand eller vand fra grundvandssænkning (kun på land), brug og udledning af kemikalier ved klargøring, CO_2 aftryk i anlægsfase samt generering af støj.

I miljøkonsekvensvurderingen for Northern Lights projektet er det er nævnt at transportsystemet skal rengøres, tryktestes og fyldes med flydende CO_2 forud for drift og injektion af CO_2 i brønden. Tryktestning sker med kvælstof. Der forventes brug af "grønne" (inkl. MEG) og "gule" kemikalier under klargøring af rørledning. Både kvælstof og kemikalier vil udledes til havet ved injektionsbrønden [40].

Lastbil, godstog, skib

Ej relevant.

9.2.3 Drift

Rørledning

Der er kun identificeret få referencer der specifikt beskriver miljøforhold ved drift af rørledning til transport af CO_2.

De miljømæssige påvirkninger under drift af ny rørledning for CO_2 vurderes at være tilsvarende dem som identificeres for typiske øvrige rørledninger anvendt til f.eks. transmission og distribution naturgas.

Der kan ved vedligeholdelses- eller reparationsarbejde skulle foretages en kontrolleret nedblæsning af sektioner med udledning af CO_2.

For rørledningen til Northern Lights gennem Hjeltefjorden, er det vurderet, at der ikke er nogen landskabelig påvirkning, da rørledningstracéet ikke er synligt [40].

I USA har der været transporteret CO_2 i over 35 år og det estimeres at over 50 millioner ton CO_2 transporteres hvert år i knap 6.000 km rørledning. Transport via rørledning ses som den mest "cost" effektive løsning, og der vurderes ikke at være barriere, hverken i forhold til design eller sikkerhed som vil kunne stå i vejen for yderligere etablering i forbindelse med udvikling af CCS [60].

Skib

Der er ikke identificeret referencer der specifikt beskriver miljøforhold ved skibstransport af CO_2.

Miljøpåvirkningen fra skibstransport i driftsfasen vil være relateret til støj samt energiforbrug og tilhørende forbrændingsemissioner og CO_2 aftryk. Herudover kan være mindre diffus udledning af CO_2 fra tanke og koblinger.

Der sker allerede i dag transport af flydende naturgas (LNG) samt af flydende petroleum gas (LPG).

Lastbil, godstog

Der er ikke identificeret referencer der specifikt beskriver miljøforhold ved lastbilstransport af CO. Miljøpåvirkningen fra lastbilstransport i driftsfasen vil være relateret til støj samt energiforbrug og tilhørende forbrændingsemissioner og CO_2 aftryk. Herudover kan være mindre diffus udledning af CO_2 fra tanke og koblinger.

Transport af CO_2 via lastbil foregår allerede i dag, og CO_2 sættevogne er derfor sikkerhedsmæssigt godkendt til vejtransport.

9.2.4 Afvikling

Rørledning

Se afsnit 8.2.4

Lastbil, godstog, skib

Ikke relevant.

9.3 Natur

9.3.1 Forundersøgelser

Se afsnit 9.2.1.

9.3.2 Anlæg og etablering

Ved etablering af CO_2-rørledninger til havs, vil der være en fysisk påvirkning af havbunden samt forstyrrelser i anlægsperioden. Se marine påvirkninger i afsnit 8.3.2.

Ved etablering af rørledninger på land, vil der være fysiske påvirkninger ved anlægsarbejde, nedgravning, trafik og øvrige påvirkninger, som kendes fra etablering af f.eks. ledninger og gasrør.

Ved Lacq pilot projekt anvendes en ca. 30 meter rørledning på land mellem fangstanlæg og onshore lagring. Rørledningen er en eksisterende gasledning, og der har derfor ikke været anlægsarbejde [48].

9.3.3 Drift

For Northern Lights projektet, er det vurderet, at CO_2-rørledningen har en relativt lille dimension og derfor ikke medfører hindringer eller påvirker fiskebestande i området. Under driftsperioden vil der årligt forekomme udslip af ca. 2 m^3 hydraulikvæske (klassificeret som "gult" kemikalie) fra ventilanlægget pr. brønd. Injektionsbrønden ligger ikke i nærheden af registrerede gydeområder, og mindre udslip af brugt vandbaseret ikke-toksisk hydraulikvæske ved test og operation af ventiler medfører ubetydelig negativ påvirkning og konsekvens for fiskeæg og yngel. [40]

Som et høringssvar til Northern Lights projektet, er det påpeget at væske i rør vil medføre støj, som bør overvåges. Operatøren henviser til, at der er et betydelig antal og længde af væsketransporterende rørledninger af varierende dimension på norsk sokkel, og at der ikke er planer om at starte støjmålinger fra CO_2-væskestrømmen i rørledningen. [62]

Ved nedgravede rørledninger på land, kan der være servitutregulerede begrænsninger af arealanvendelsen over og omkring rørledningen, som kan påvirke natur og biodiversitet.

9.3.4 Afvikling

Se afsnit 9.2.4.

10 Referencer

[1]	KEFM, »Principaftale mellem regeringen (Socialdemokratiet), Venstre, Dansk Folkeparti, Radikale Venstre, Socialistisk Folkeparti, Enhedslisten, Det Konservative Folkeparti, Liberal Alliance og Alternativet om En køreplan for lagring af CO2,« Juni 2021 2021. [Online]. Available: https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&ved=2ahUKE-wiQ3-Pky_HyAhWIz4sKHWjmD5sQFnoECAYQAQ&url=https%3A%2F%2Fkefm.dk%2FMe-dia%2F637606718216961589%2FPrincipaftale%2520om%2520CO2-lagring.pdf&usg=AOvVaw1y6rm60I85JFg7tfo1qR0P. [Senest hentet eller vist den September 2021].
[2]	Global CCS Institute, »Global status of CCS 2020,« 2020. [Online]. Available: https://www.globalccsinstitute.com/resources/global-status-report/. [Senest hentet eller vist den August 2021].
[3]	Energistyrelsen, »Leverance 5.1: Miljø- og sikkerhedsaspekter i CCS-kæden,« København V, 2021.
[4]	Global CCS Institute, »Global CCS Institute facilities database,« 2021. [Online]. Available: https://co2re.co/ClimateChange.
[5]	C. Bofeng og e. al, »China Status of CO2 Capture, Utilization and Storage (CCUS) 2019,« Center for Climate Change and Environmental Policy,Chinese Academy of Environmental Planning. 2020, 2019.
[6]	K. M. Novak, N. Gaurina- Medimurec og L. Herncevic, »Significance of enhanced oil recovery in CO2 emission reduction,« Sustainability, årg. 13, 2021.
[7]	A. Hosa, M. Esentia, J. Stewart og S. Haszeldine, »Benchmarking worldwide CO2 saline aquifer injections,« March 2010. [Online]. Available: https://www.sccs.org.uk/images/expertise/reports/working-papers/wp-2010-03.pdf.
[8]	Scottish Carbon Capture & Storage (SCCS), »Global CCS Map,« [Online]. Available: https://www.sccs.org.uk/expertise/global-ccs-map.
[9]	ArkerSolutions, »Arker Solutions starts CCS test program at Preem Refinery in Sweden,« may 2020. [Online]. Available: https://www.akersolutions.com/news/news-archive/2020/aker-solutions-starts-ccs-test-program-at-preem-refinery-in-sweden/. [Senest hentet eller vist den August 2021].
[10]	Det Norske Veritas, »Design and operation of CO2 pipelines,« 2010.
[11]	F. H. Hedlund, »The extreme carbon dioxide outburst at the Menzengraben potash mine 7 July 1953,« Elsevier, 2011.
[12]	P. Harper, »Assessment of the major hazard potential of carbon dioxide (CO2),« Health and Safety Executive, 2011.
[13]	S. Gant, M. Pursell, A. McGillivray, J. Wilday, M. Wardman og A. Newton, »Overview of carbon capture and storage (CCS) projects at HSE's Buxton Laboratory,« Health and Safety Executive, 2017.
[14]	A. McGillivray og J. Wilday, »Comparison of risks from carbon dioxide and natural gas pipelines,« Health and Safety Laboratory , 2009.
[15]	J. L. Lewicky, J. Birkholzer og C.-f. Tsang, »Natural and industrial analogues for leakage of CO_2 from storage reservoirs: identification of features, events, and processes and lessons learned,« Ernest Orlando Lawrence Berkeley National Laboratory , 2006.
[16]	C. Oldenbrug og L. Pan, »Major CO2 blowouts from offshore wells are strongly attenuated in water deeper than 50 m,« Energy Geosciences Division - Lawrence Berkeley National Laboratory, 2019.
[17]	Equinor, »Northern Lights FEED Report,« Equinor, 2020.

[18]	F. H. Hedlund, »Past explosive outbursts of entrapped carbon dioxide in salt mines provide a new perspective on the hazards of carbon dioxide,« Intelligent Systems and Decision Making for Risk Analysis and Crisis Response, 2013.
[19]	P. J. Rew, P. Gallagher og D. M. Deaves, »Dispersion of subsea releases, review of prediction methodologies,« HSE BOOKS, HSE Executive- offshore technology report, 1995.
[20]	IEAGHG, »Environmental impacts of amine emissions during post combustion capture - Workshop 2010/11,« International Energy Agency Environmental Projects Ltd., Cheltenham, UK, 2010.
[21]	J. L. M. Gibbins, »BAT Review for New-Build and Retrofit Post-Combustion Carbon Dioxide Capture Using Amine-Based Technologies for Power and CHP Plants Fuelled by Gas and Biomass as an Emerging Technology under the IED for the UK,,« 2021. [Online]. Available: https://ukccsrc.ac.uk/best-available-technology-bat-information-for-ccs/. [Senest hentet eller vist den august 2021].
[22]	M. Bui, C. S. Adjiman, A. Bardow, E. J. Anthony, A. Boston, S. Brown, P. S. Fenell, S. Fuss, A. Galindo, L. A. Hackett, J. P. Hallett, H. J. Herzog, G. Jackson, J. Kemper, S. Krevor, G. C. Maitland, M. Matuszewski, I. S. Metcalfe, C. Petit, G. Puxty, J. Reimer, D. M. Reiner, E. S. Rubin, S. A. Scott, N. Shah, B. Smit, J. P. M. Trusler, P. Webley, J. Wilcox og N. M. Dowell, »Carbon capture and storage (CCS): the way forward,« Energy and Environmental Science, årg. 11, pp. 1062-1176, 2018.
[23]	ECHA (europa.eu), »Information om kemikalier - ECHA (europa.eu).,« 2021. [Online]. Available: https://echa.europa.eu/da/information-on-chemicals.
[24]	E. Gjernes, L. I. Helgesen og Y. Maree, »Health and environmental impact of amine based post combustion CO_2 capture,« Energy Procedia, årg. 37, pp. 735-742, 2013.
[25]	G. Dautzenberg og T. Bruhn, »Environmental impacts from CCS technologies,« Institute for Advanced Sustainability Studies, Potsdam, 2013.
[26]	Gassnova, »Developing longship - Key lessons learned,« 2020.
[27]	L. I. Helgesen og E. Gjernes, »A way of qualifying Amine Based Capture Technologies with respect to Health and Environmental Properties,« Elsevier, Energy Procedia, p. 13, 2016.
[28]	Scottish Environment Protection Agency, »Review of amine emissions from carbon capture (version 2.01),« Natural Scotland - Scottish Government, 2015.
[29]	Aker Carbon Capture, »Experience-based approaches to lower carbon cement production - How the Brevik CCS project opens up new possibilities for other cement producers,« Aker Carbon Capture Norway AS, Lysaker, 2021.
[30]	K. Fujita, Y. Kato, S. Saito, H. Kitamura, D. Muraoka, M. Udatsu, Y. Handa og K. Suzuki, »The effect of aerosol characteristics in coal- and biomass-fired flue gas on amine emissions,« 14th International Conference on Greenhouse Gas Control Technologies, GHGT-14, pp. 1-10, 2018.
[31]	Ministry of Petroleum and Energy, »Feasibility study for full-scale CCS in Norway,« Gassnova & Gassco, 2016.
[32]	NIPH, »Health effects of amines and derivatives associated with CO_2 capture: Nitrosamines and nitramines,« 2011. [Online]. Available: https://www.fhi.no/publ/2011/health-effects-of-amines-and-deriva/.
[33]	UK Environmental Agency, »Guidance, Post-combustion carbon dioxide capture: best available techniques (BAT),« july 2021. [Online]. Available: https://www.gov.uk/guidance/post-combustion-carbon-dioxide-capture-best-available-techniques-bat#who-this-guidance-is-for. [Senest hentet eller vist den August 2021].
[34]	M. N. Toftegaard, »OxyFuel combustion of coal and biomass,« 2011.
[35]	Total, »Carbon capture and storage, the Lacq pilot, project and injection period 2006-2013,« 2014.

[36]	IEAGHG, »Evaluation of reclaimer sludge disposal from post combustion CO2 capture,« 2014.
[37]	Rambøll, »CO2 fangst på danske affaldsenergianlæg,« København, 2020.
[38]	European Environment Agency, »Air pollution impacts from carbon capture and storage (CCS),« 2011.
[39]	T. Lecomte, J. F. F. d. l. Fuente, F. Neuwahl, M. Canova, A. Pinasseau, I. Jankov, T. Brinkmann, S. Roudier og L. D. Sancho, »Best Available Techniques (BAT) Reference Document for Large Combustion Plants,« 2017.
[40]	Equinor, »EL001 Northern Lights - Mottak og permanent lagring af CO2. Plan for utbygging, anlegg og drift. Del II - Konsekvensutredning.,« Oktober 2019.
[41]	L. Eilertsen, »Northern Lights. Konsekvensvurdering med hensyn på naturmiljø og biologisk mangfold på land,« Rådgivende Biologer AS, 2018.
[42]	MAERSK OIL DBU, »Redegørelse for miljømæssige og sociale virkninger - ESIS-Tyra,« Rambøll, 2017.
[43]	Energistyrelsen, »Standard vilkår for forundersøgelser til havs,« 2017.
[44]	Energistyrelsen, »Guidelines for drilling, esploration,« 1988,2009.
[45]	A.-K. Furre, O. Eiken, H. Alnes, J. N. Vevatne og A. F. Kier, »20 years of monitoring CO2-injection at Sleipner,« Elsevier, p. 3916 – 3926, 2017.
[46]	Erhvervsministeriet, »Cirkulære om naturgaslager ved Stenlille,« Erhvervsministeriet , 1991.
[47]	M. Roskilde, »Revurdering af miljøgodkendelser Stenlille gaslager,« Miljøministeriet, 2009.
[48]	Total, »Carbon capture and storage, The Lacq pilot - results and outlook,« 2013.
[49]	S. E. Greenberg, »Illinois Basin Decatur Project,« 2015.
[50]	M. Batres, F. M. Wang, H. Buck, R. Kapila, U. Kosar, R. Licker, D. Nagabhushan, E. Rekhlman og V. Suarez, »Environmental and climate justice and technological carbon removal,« The Electricity Journal, nr. 34, 2021.
[51]	L. A. Kyhn, S. Wegeberg, D. Boertmann, P. Aastrup, J. Nymand og A. Mosbech, »Onshore Seismic Surveys in Greenland,« Aarhus University, DCE – Danish Centre for Environment and Energy, 2020.
[52]	M. Hjorth, L. D. Kristensen, C. J. Murray, J. H. Andersen, S. Brooks og K. Sørensen, »Effects of oil and gas production on marine ecosystems and fish stocks in the Danish North Sea,« WSP Denmark, NIVA, Teknologisk Institut, 2021.
[53]	Søfartsstyrelsen, »Miljøvurdering af Danmarks Havplan,« COWI, 2021.
[54]	A. D. Nielsen, N. P. Christensen, P. Jørgensen og E. L. Lundsteen, »Catalogue of geological storage of CO2 in Denmark, Danish Energy Agency,« Rambøll, Copenhagen, 2021.
[55]	P. Deda, M. Elbertzhagen og M. Klussmann, »Light Pollution and the Impacts on Biodiversity, Species and their Habitats,« Everglades, nr. Secretariat of the Convention on the Conservation of Migratory Species of Wild Animals (UNEP-CMS), pp. 133-138, 2007.
[56]	J. M. Neff, »Fate and effects of water based drilling muds and cuttings in cold water environments.,« Review prepared for Shelle exploration an Production Company Houston Texas, 2010.
[57]	T. Bakke, J. Klungsøyr og S. Sanni, »Environmental impacts of produced water and drilling waste discharges from the Norwegian offshore petroleum industry,« Marine Environmental Research, årg. 92, pp. 154-169, 2013.
[58]	K. Wallmann, M. Haeckel, P. Linke, L. Haffert og M. Schmidt, »Best Practice Guidance for Environmental Risk Assessment for offshore CO2 geological storage,« EU: ECO2 - Sub-seabed CO2 Storage: Impact on Marine Ecosystems, 2015.

[59]	ZEP, »CO2 Storage Safety in the North Sea: Implications of the CO2 Storage Directive - TWG Collaboration across the CCS Chain,« European Zero Emission Technology and Innovation Platform, 2019.
[60]	US Office of Fossil Energy and Carbon Management, »Report of the Interagency task force on Carbon Capture and Storage,« 2010.
[61]	EcoWatch, »How the World's First CO2 Pipeline Explosion Turned a Mississippi Town Into 'a Zombie Movie',« August 2021. [Online]. Available: https://www.ecowatch.com/co2-pipeline-explosion-mississippi-2654814127.html.
[62]	Equinor , »EL001 Northern Lights: Plan for utbygging, anlegg og drift - Del II: Konsekvensutredning - Oppsummering av høringsuttalelser og tilsvar til disse,« Equinor ASA, Stavanger, 2020.
[63]	Energistyrelsen og Energinet, »Technology Data - Industrial process heat,« 2020.
[64]	Energistyrelsen og Energinet, »Technology data - Energy transport,« 2017.
[65]	EIGA, »MINIMUM SPECIFICATIONS FOR FOOD GAS APPLICATIONS, Doc 126/20,« EUROPEAN INDUSTRIAL GASES ASSOCIATION, 2020.
[66]	H. J. Herzog, Carbon Capture, 2018.
[67]	S. Flude. [Online]. Available: https://theconversation.com/carbon-capture-and-storage-has-stalled-needlessly-three-reasons-why-fears-of-co-leakage-are-overblown-130747.
[68]	The Danish Hydrocarbon Research and Technology Centre, »CO2 storage in Danish Oil & Gas fields,« DTU, Kongens Lyngby, 2020.
[69]	Project Greensand, »Project Greensand,« [Online]. Available: https://statics.teams.cdn.office.net/evergreen-assets/safelinks/1/atp-safelinks.html.
[70]	Søfartsstyrelsen, »Danmarks havplan,« 2021. [Online]. Available: https://havplan.dk/da/page/info. [Senest hentet eller vist den 23 august 2021].
[71]	Maersk Drilling, »MaerskDrilling,« [Online]. Available: https://www.maerskdrilling.com.
[72]	EU, »Directive 2009/31/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL, of 23 April 2009 on the geological storage of carbon dioxide and amending Council Directive 85/337/EEC, European Parliament and Council Directives 2000/60/EC, 2001/80/EC, 2004/35/EC, 2006,« 2009. [Online].
[73]	T. Dahl-Jensen, R. Jakobsen, T. B. Bech, C. M. Nielsen, C. N. Albers, P. H. Voss og T. B. Larsen, »Monitoring for seismological and geochemical groundwater effects of high-volume pumping of natural gas at the Stenlille underground gas storage facility, Denmark,« GEUS Bulletin, p. 8, 2021.
[74]	Energistyrelsen, »Technology Data - Energy transport,« 2020.

Bilag A Teknisk beskrivelse af CCS anlæg

Afsnittet indeholder en teknisk beskrivelse af de forskellige anlæg, der indgår i CCS omfattende 1) geologisk lagring, 2) CO_2-fangst, 3) mellemlagring samt 4) transport infrastruktur. For hvert anlæg indgår en teknisk beskrivelse af faserne a) forundersøgelser, b) anlæg og etablering, c) drift og d) afvikling.

A.1 CO_2-fangstanlæg

CO_2-fangstteknologier afgrænses specifikt til følgende typer anlæg med høj teknologisk modenhed, som allerede er eller er tæt på at være kommercielt tilgængelige:

- Rensning af røggas (post combustion) ved hhv. aminvask og nedkølet ammoniak (oftest benævnt chilled ammonia)

- Dannelse af røggas med høj CO_2 koncentration ved forbrænding ved iltrige betingelser (oxyfuel).

Det forudsættes desuden, at der etableres liquefaction-anlæg samt mellemlagerfaciliteter ved efterfølgende transport med lastbil, tog eller skib, alternativt kompressortrin og dehydrering ved transport via rørledning.

Følgende tekniske beskrivelse af disse anlæg og transportkæder dækker forundersøgelser, anlæg, drift og afvikling. Der henvises desuden til Energistyrelsens teknologikataloger for hhv. procesvarme og carbon capture samt transport af energi og CO_2 [63], [64].

A.1.1 Forundersøgelser

Specifikt for selve fangstanlægget vil der for alle de beskrevne procestyper skulle foregå forundersøgelser som for typiske industri-/procesanlæg. Desuden skal der pga. det høje energiforbrug til selve CO_2-fangsten foretages undersøgelse af udnyttelse af evt. eksisterende spildvarme fra hovedprocessen, samt integration med damp- og fjernvarmesystemer for at sikre høj energieffektivitet. Herunder skal behovet for køleeffekt afdækkes, idet processen vil kræve en del kølevand og/eller -luft. Da røggassen indeholder en række stoffer, som er uhensigtsmæssige i CO_2-fangstprocessen, skal der afhængigt af koncentrationsniveauer muligvis etableres yderligere rensetrin såsom røggaskondensering med lud og / eller deNOx.

Ved et retrofit af CO_2-fangst på et eksisterende anlæg vil der desuden ske ændring af røggastemperatur, flow og vandmætning, der influerer på spredning af røggassen.

A.1.2 Anlæg og etablering

Anlæg og etablering vil for alle de beskrevne procestyper skulle foregå som for typiske industri-/procesanlæg.

Konstruktion af kemikalietanke mv. skal sikre at der ikke kan se forurening af jord, grundvand og overfladevand ved eventuelt spild. Specielt for aminvask bemærkes, at de typisk anvendte aminer er skadelige for vandmiljøet.

Konstruktion af lagertanke mv. for CO_2 skal sikres mod eventuelle lavpunkter og lukkede miljøer, hvor CO_2 kan opkoncentreres ved eventuel lækage

Der skal desuden sikres tilstrækkelig rumventilation samt CO_2-detektorer/alarmer i bygninger og lavpunkter i terrænet, hvor der er risiko for ophobning.

A.1.3 Drift

Beskrivelse af teknologier – CO_2-fangst

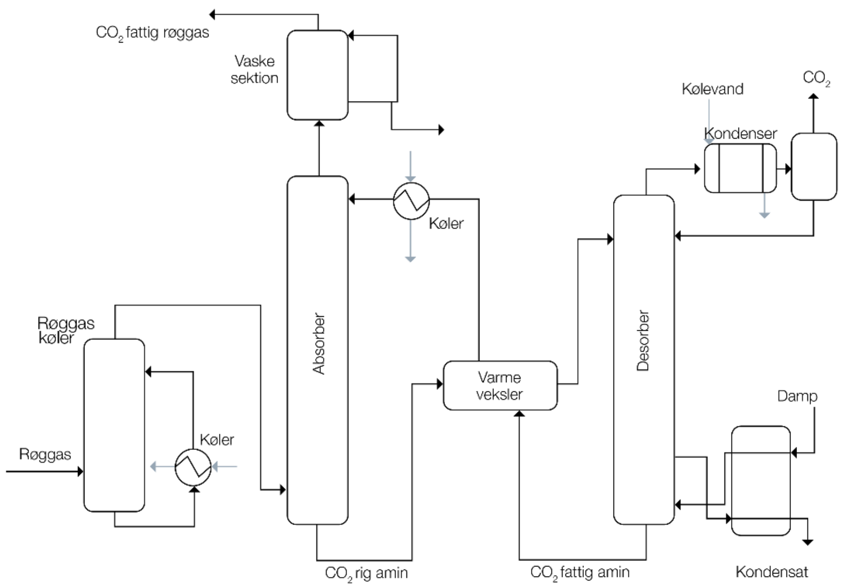
Aminvask
Aminvask hører under post combustion typen, hvor CO_2 adskilles fra en gasstrøm. Metoden benyttes f.eks. ved produktion af CO_2 til fødevarer samt til opgradering af biogas og naturgas, og vil være relevant til fangst af CO_2 fra røggassen efter forbrænding i kedler/ovne. Et procesdiagram ses i Figur 3 nedenfor.

Røggassen fra forbrændingsprocessen eller anden CO_2-holdig gas renses, køles og ledes til en absorber, hvor den skrubbes med en vandig amin-opløsning. CO_2 i røggassen optages af aminen under frigivelse af varme, hvorefter den CO_2-fattige røggas passerer en vaskesektion og et dråbefang for at fjerne amin samt nedbrydningsprodukter fra aminen, inden røggassen udledes via skorstenen. Der opnås typisk en gennemsnitlig effektivitet på 90 %, dvs. 90 % af CO_2-indholdet i den indgående røggas opfanges.

Den CO_2-rige amin ledes herefter til en desorber, hvor den opvarmes vha. damp, og CO_2 frigives i koncentreret form. Den CO_2-fattige, varme amin veksles med den køligere CO_2-rige amin, køles yderligere og returneres til absorberen til fornyet optagelse af CO_2. Selve den koncentrerede CO_2-strøm køles, herved dannes kondensat som ledes tilbage til processen.

Dampkilden findes på hovedanlægget ved udnyttelse af evt. overskudsvarme, samt udtag fra turbine eller hoveddampsystem. Alternativt etableres en hjælpekedel, hvis der ikke er tilstrækkelig til rådighed. Varme fra produceret i CO_2-fangstprocessen vil i nogen grad kunne anvendes i fjernvarmenettet.

Aminen vil over tid ophobe en række affaldsprodukter. Disse kan i nogen udstrækning fjernes ved destillation eller ionbytning i en reclaimer. Der vil herunder dannes hhv. en slamfraktion eller spildevand. Den termisk destillation danner en slamfraktion, der må forventes at blive klassificeret som farligt affald [36]. Tilsvarende giver ionbytteren anledning til spildevand, når resinerne regenereres med opløsninger af lud (NaOH) og svovlsyre (H_2SO_4.)



Figur 3: Processkitse af aminvask. Reclaimeren er ikke vist.

Ved retrofit af CO_2-fangst på en eksisterende punktkilde muliggør en post combustion løsning kortere driftsstop af det eksisterende anlæg i anlægsfasen, da der primært er behov for ændringer af røggaskanaler samt damp- og varmeintegration. Udfordringer for aminvask er primært følsomheden over for forurenende stoffer i røggassen såsom svovldioxid (SO_2), nitrogendioxid (NO_2), saltsyre (HCl) og partikler, samt det høje energibehov. Teknologien er moden og kommercielt tilgængelig – dog primært for kapaciteter på 1-15 ton/h CO_2 indfanget.

Enkelte større anlæg er bygget i hhv. USA og Canada:

- Kulfyret anlæg, Petra Nova, USA, 1.600.000 ton pr år. 200 ton/h (MHI)
- SaskPower Boundary Dam, Canada (Shell CanSOLV), 400.000 ton/år (50 ton/h)

De enkelte leverandører af aminbaserede CO_2-fangstanlæg benytter i stor udstrækning egne, hemmeligholdte aminblandinger med forskellige forbedrede egenskaber såsom lavere degradering og energiforbrug. Den kommercielt tilgængelige amin monoetanolamin (MEA) er kendetegnet ved et højt energiforbrug, der ligger 50% over, hvad flere leverandører har angivet at kunne opnå med deres egne blandinger. Andre typisk anvendte aminer er bl.a. dietanolamin (DEA), metyldietanolamin (MDEA), piperazin (PZ), 2-Amino-2-metylpropanol (AMP), diglykolamin (DGA) og diisopropanolamin (DIPA).

Chilled ammonia

Chilled ammonia processen er også af post combustion typen og ligner aminvask i udformningen. Processen er demonstreret i relativt stor skala, 110.000 ton pr.

år, på Mountaineer demoanlægget i USA. Den er dermed tæt på kommerciel lancering.

Der benyttes en vandig ammoniakopløsning i stedet for amin typisk i en opløsning under 25%. Da reaktionsoptimum er mellem 5 °C og 15 °C, skal røggassen køles til dette temperaturinterval. Fordele er angiveligt reduceret energiforbrug, CO_2-produkt ved relativt høje tryk (5-25 bar) samt fravær af amin og nedbrydningsprodukter i røggassen. Imidlertid har varmebehovet vist sig at være højere end forventet, og problemstillinger såsom langsom absorptionskinetik, øget proceskompleksitet samt udfordringer med håndtering af udfældninger af salte er også identificeret, hvilket giver ustabil drift og korrosion. Desuden skal der udføres yderligere afkøling af røggassen sammenlignet med en aminproces.

Oxyfuel
Oxyfuel er en væsentligt anderledes teknologi, idet der foretages forbrænding i ilt fortyndet med recirkuleret røggas. Dette giver en røggas bestående hovedsageligt af CO_2 og vand. Efter kedlen renses røggassen for vanddamp og andre urenheder, og den resulterende gas med høj CO_2-koncentration kan herefter komprimeres. På grund af luftindtrængning i systemet, behov for iltoverskud, kvælstof i brændslet mv. vil den resulterende, tørre CO_2-koncentration ligge på 70 - 90%.

Ilt til forbrænding produceres ved adskillelse fra atmosfærisk luft med en luftseparationsenhed, hvilket er kendt teknologi. For at sikre ilt til opstart og løbende forbrænding vil der være behov for en buffertank med flydende ren ilt.

Ved retrofit med oxyfuel kræves væsentlige ændringer af det eksisterende anlæg, herunder ombygning af ovn/kedel og tætning af røggassystemet. Dette er nødvendigt, da gassens egenskaber og de termodynamiske betingelser ændres, hvilket blandt andet påvirker forbrændingszonen og varmeoverføringen. Den største udfordring ved retrofit er dog at reducere luftlækager ind i systemet mest muligt.

Der eksisterer ikke egentlige anlæg på kommerciel skala, men en række demoanlæg på kul (Schwarze Pumpe, 30 MW_{th} og Callide i Australien, 120 MW_{th}) har tidligere været i drift. Der er desuden en række eksperimentelle fluid bed kedler (CFB'er) på typisk få MW_{th} - dog et enkelt på 30 MW_{th} i Spanien.

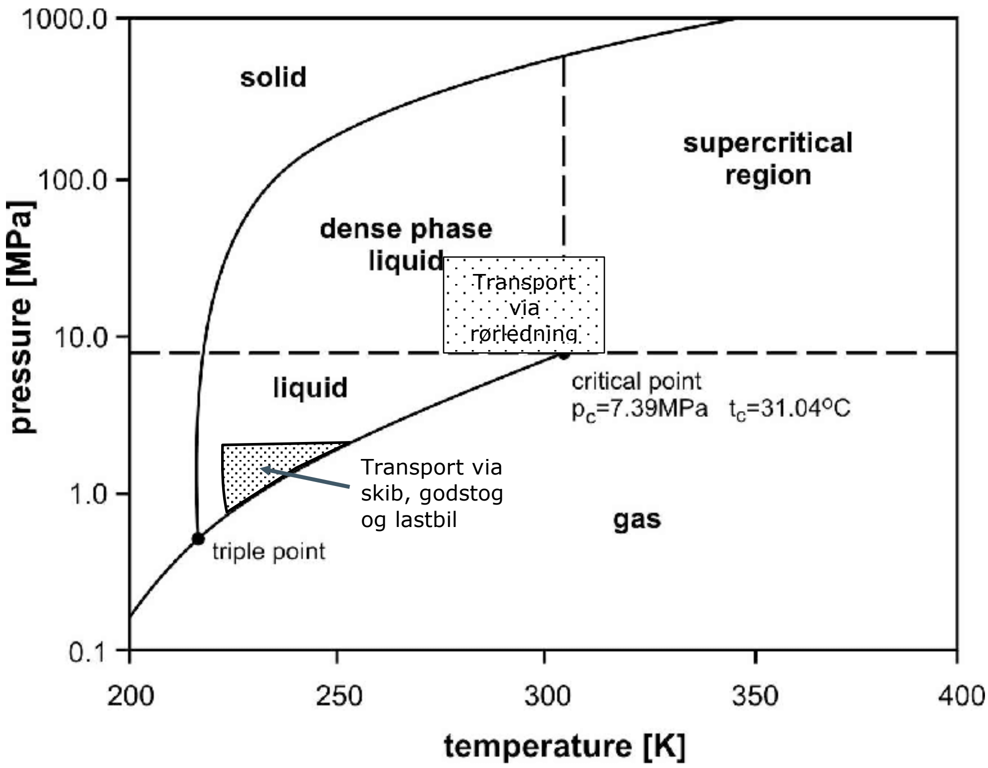
Beskrivelse af teknologier – CO_2-konditionering

Efter fangst og dannelsen af en koncentreret CO_2-strøm skal der alt efter den valgte transportmetode ske komprimering og evt. kondensering/liquefaction, se Figur 4.

Komprimering
Ved transport via rørledning skal CO_2 komprimeres vha. en flertrinskompressor med intercooling, hvor den genererede varme kan udnyttes andre steder i processen. Typiske CO_2-rørledningstryk på længere strækninger er 80-150 bar for at undgå tofase-regionen af fasediagrammet, samt opnå en tilfredsstillende den-

sitet. Ved transport på kortere strækninger (såsom 10-20 km) kan lavere trykniveauer være fordelagtige. Over jord vil det være ca. 10 bar for at undgå CO_2-kondensation ved lave omgivelsestemperaturer. For nedgravede rør, hvor der er frostfrit, kan der gås op til 30 bar.

CO_2 er korrosiv ved tilstedeværelse af fugt, da der dannes kulsyre, og i kombination med høje tryk kan der desuden ske udfældning af gashydrater. Derfor er dehydrering af gassen til et fugtindhold under 50-400 ppmv nødvendigt. Dehydrering sker typisk som en kombination af to forskellige kølesystemer – vandkøling og en flydende glykolproces. Et mekanisk filter er monteret efter absorptionskolonnen for at fjerne eventuelle partikler, der rives med i CO_2-strømmen. Tørring installeres ved et mellemliggende trin i kompressoren.



Figur 4: Fasediagram for CO_2. Områder for transport med skib, godstog og lastbil i flydende form, samt transport via rørledning i komprimeret tilstand er angivet med skraverede områder. 1 MPa = 10 bar. 250 K = -23 ℃.

Kondensering / liquefaction
Ved kondensering (også kaldt liquefaction) komprimeres og afkøles CO_2-strømmen til ca. 15-18 bar og -21 til -27 ° C.

CO_2-produktstrømmen ledes først gennem en køler og separator for at fjerne vand, før gassen komprimeres i kompressoren. CO_2-gassen afkøles derefter yderligere og vaskes i en skrubbersektion for at fjerne vandopløselige urenheder og tilbageværende amin. Vasketrinet kræver vand som efterfølgende skal håndteres ved f.eks. recirkulering til fangstanlægget, internt procesvand eller behandling i renseanlæg. Yderligere tørring sker vha. en absorptionskolonne til meget lavt niveau (<50 ppm) for at undgå korrosionsproblemer i rør og lagertanke, samt dannelse af iskrystaller. Afhængig af kravene til renheden af CO_2-produktet, kan forskellige adsorbere og filtre installeres nedstrøms, f.eks. et aktivt kulfilter. Den tørre CO_2-gas køles derefter, inden den kommer ind i destillationskolonnen, hvor inerte / ikke-kondenserbare gasser, såsom kvælstof, ilt og argon fjernes, mens CO_2 kondenseres med en ekstern køler (typisk ammoniak). Flydende CO_2 sendes til opbevaring i isolerede tryktanke.

Et standard kondenseringsanlæg er normalt designet til at producere CO_2 i fødevarekvalitet, hvilket betyder, at forskellige rensetrin er inkluderet, såsom aktivt kulfilter, NO_X-fælde osv., for at fjerne sporkomponenter fra aminvask eller lignende. Den producerede CO_2 har typisk en renhed over 99,9 vol%.

Overordnet drift af fangst og konditionering
Under drift overholdes de gængse sikkerhedsregler for de øvrige anlæg. Ved kondenseringsanlægget er der desuden risiko for forfrysninger ved direkte kontakt. Ved arbejde hvor der kan ske kontakt med CO_2, anvendes sikkerhedsbriller og kuldeisolerende handsker.

For aminvask skal der under påfyldning af aminer samt håndtering af kemiske restprodukter fra aminvask-processen anvendes personlige værnemidler samt sørges for tiltag til at undgå spild og udledning til omgivelserne. Affaldet fra reclaimer-processen vil skulle bortskaffes som farligt affald eller afbrændes på hovedanlægget, såfremt der er tale om den termiske type. Ionbyttertypen vil kræve spildevandsbehandling.

For chilled ammonia skal der tilsvarende være foranstaltninger ved påfyldning af ammoniak (NH_3), der er giftig. Mht. oxyfuel skal der sikres mod lækager af ilt, da gassen er stærkt brandnærende.

Aminvasken medfører emissioner til luft. De specifikke emissioner vil være afhængig af den valgte metode, hvilke aminer som anvendes og af røggassen fra den specifikke punktkilde.

I røggassen kan der forekomme emissioner af amin samt nedbrydningsprodukter som ammoniak (NH_3) og flygtige organiske stoffer (VOC).

Nogle aminer kan desuden danne toksiske nitrosaminer ved reaktion med NO_X.

Ved tilstedeværelse af høje koncentrationer af f.eks. svovlsyre og submikrone partikler i røggassen kan der desuden dannes aminholdige aerosoler. Vasketrin og dråbefang efter absorberen mindsker disse emissioner, men evt. aerosoler fjernes dog ikke effektivt.

Tilsvarende er det for chilled ammonia processen primært udledning af ammoniak, der skal undgås.

Mht. spildevand dannes det ved post combustion typerne ved vandoverskud i systemet. Ligeledes haves vaskevand fra absorberens røgvasketrin og rensning af CO_2-strømmen. Vandet vil skulle behandles i et renseanlæg før udledning eller anvendes som internt procesvand. For oxyfuel udkondenseres større mængder vand fra røggassen, hvilket dog er tilsvarende ved normal forbrænding. Dette vand skal renses som typisk røggaskondensat.

Specielt for kondenseringen af CO_2, kan køleenheden indeholde ammoniak (NH_3), hvilket kræver sikkerhedsudstyr og potentielt andre sikkerhedsmæssige forholdsregler.

Beskrivelse af teknologier - CO_2-kvalitet

Den følgende specifikation for CO_2 i forbindelse med lagring i undergrunden, er blevet defineret for Northern Lights projektet [17]. I kilden anføres, at såfremt CO_2 kvaliteten afviger fra det angivne, skal der udføres en risikovurdering for installationerne.

Tabel 4: Specifikation for CO_2 i forbindelse med lagring i undergrunden på Northern Lights projektet [17]

Komponent	Max. koncentration vppm	Årsag
Vand, H_2O	30	Undgå dannelse af hydrater og udfældning af frit vand i anlægsdele til transport og mellemlagring. Minimere risikoen for blokering og korrosion.
Oxygen, O_2	10	Sat for at opfylde kravene til renhed ved slutlagring. O_2 kan forårsage korrosion, når det reagerer med klorider (Cl).
Svovl oxider, SOx	10	SOx accelerer korrosion i nærvær af vand.
Nitrogen oxider, NO_X	10	NO_X accelerer korrosion i nærvær af vand.
Hydrogen sulfid, H_2S	9	Giftig ved indånding. Niveau indstillet til at reducere risikoen for mulig lækage.
Carbon monoxid, CO	100	Giftig ved indånding. Niveau indstillet til at reducere risikoen for mulig lækage.
Amin	10	Har potentiale til at reagere med og nedbryde ikke-metalliske materialer
Ammoniak, NH_3	10	-
Hydrogen, H_2	50	H_2 kan forårsage korrosion i form af brintskørhed.
Formaldehyd, HCHO	20	Kan reagere med ilt til myresyre.
Acetaldehyd	20	Kan reagere med ilt til eddikesyre.
Kviksølv, Hg	0,03	Giftig for personalet. Kan forårsage skørhed i metalliske materialer.
Cadmium, Cd + Thallium, Tl	0,03 (sum)	Giftig for personalet. Kan forårsage skørhed i metalliske materialer.

Til sammenligning kan f.eks. nævnes fødevarekvalitet standard for CO_2 (E290) ifølge EU og EIGA [65].

Tabel 5 Fødevarekvalitet standard for CO_2 (E290) er ifølge EU og EIGA [65]

Komponent	CO_2 (E290)
Analyse CO_2 (v/v)	>99 v%
Vand	<52 vppm
CO	<10 vppm
Totale hydrocarboner	<50 vppm
Olie-indhold	<5 mg/kg
Surhed og reducerende stoffer	Bestå test

A.1.4 Afvikling

Afvikling vil skulle forberedes og effektueres som for andre typiske industri-/procesanlæg. Anlæggene skal tømmes og demonteres, eventuelle bygninger skal nedrives og området eventuelt genetableres. Der er tale om velkendte operationer og anlægsdele som i nogen udstrækning kan afsættes kommercielt.

A.2 Mellemlager-faciliteter

Mellemlager-faciliteter etableres typisk i nærheden af CO_2 punktkilderne og på eller i umiddelbar nærhed af havne- og/eller industriområder, hvor transport med skib eller lastbil er mulig. Mellemlager-faciliteter vil formentlig omfatte kondensering / liquefaction-faciliteter (beskrevet tidligere) og lagring i tanke.

A.2.1 Forundersøgelser

Der forudses ikke særlige tekniske forundersøgelser i forbindelse med et mellemlager. Sikkerhedsforanstaltninger for at forhindre læk, samt minimering af udslip ved uheld skal vurderes.

A.2.2 Anlæg og etablering

Anlæg og etablering skal foregå som typisk for industrilagre. Dog skal der for CO_2 lagertanke ikke opstilles spildbarrierer som for andre kemikalietanke.Der er her behov for at undgå lavpunkter og lukkede miljøer.

A.2.3 Drift

Mellemlageret er nødvendig som buffer mellem den kontinuerte produktion af CO_2 og den diskontinuerte lastbils- og skibstransport. Der kan være behov for mellemlagre både ved CO_2-fangstanlægget og ved eventuelt udskibningssted.

Lagerkapaciteten vil afhænge af lastbilernes eller skibenes cyklustid sat i forhold til produktionen. Den maksimale størrelse af tankene vil være begrænset af, hvad der er praktisk at transportere fra tankleverandør til installationsstedet. For mindre kapaciteter under 100 m³ fås isolerede standardtanke. Kugletanke kan fremstilles med en enhedsstørrelse på 1.000 m³ eller mere, men disse er for store til vejtransport og kræver derfor adgang til en havn eller konstruktion af de store tanke på selve sitet. Ved CO_2-terminaler med lagerkapacitet på flere 1.000 m³ vil mellemlageret bestå af flere tanke. Det vil dog primært afhænge af det enkelte projekt, hvad der er hensigtsmæssigt.

Lagertanke til flydende CO_2 vil være udstyret med et import- / eksportrør samt et gasreturrør. Det vil dog være muligt at isolere hver enkelt tank fra systemet ifm. vedligehold, men der skal dog ske overvejelse omkring forringelse af tankenes levetid ved store temperaturgradienter. Typisk tages kryogene lagertanke ikke ud af drift. For at holde lagertankene afkølede, fordampes en lille del af den flydende CO_2 kontinuerligt. Gassen returneres derefter til kondenseringsanlægget, eller udledes til omgivelserne såfremt liquefaction-anlægget er ude af drift eller der ikke er tilknyttet kondensering til det pågældende mellemlager. En CO_2 udluftningsventil installeres for at muliggøre kontrolleret udluftning fra lagertankene og dermed fastholde trykket, når kondenseringsanlægget ikke er i drift. Eksportsystemet består af en hovedrørledning til et antal pumper. Rørledningen føres til en lastestation til enten skib, tog eller lastbil. Parallelt med påfyldningssystemet kan der installeres et retursystem til at føre fortrængte CO_2-gas fra skibene tilbage til lagertankene. Derudover ledes rørledningen tilbage til kondenseringsanlægget, hvilket muliggør rekondensering af den fortrængte CO_2-gas. Systemet skal udstyres med sikkerhedsventiler. Der vil skulle være fokus på vedligehold og korrosionsovervågning for at sikre mod utilsigtede udslip af CO_2 fra mellemlageret.

A.2.4 Afvikling

Afvikling vil skulle forberedes og effektueres som for andre typiske industrilagre. Anlæg og tanke skal tømmes og demonteres, eventuelle bygninger skal nedrives og området eventuelt genetableres. Der er tale om velkendte operationer og anlægsdele som i nogen udstrækning kan afsættes kommercielt.

A.3 Geologisk lagring af CO_2 på land og til havs.

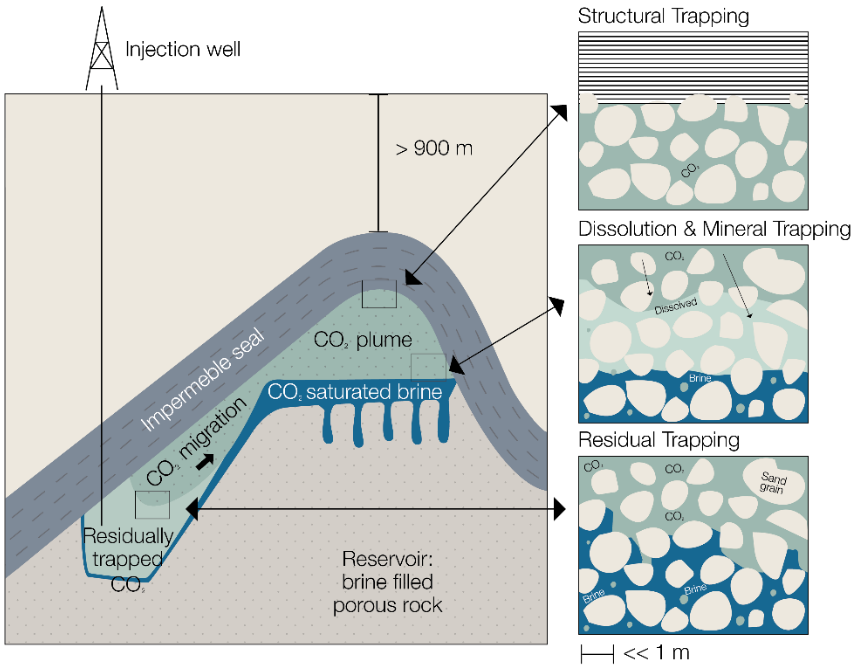
Geologisk CO_2 lager - grundlæggende forudsætninger

Et geologisk lager består af en række elementer; et reservoir dvs. et geologisk lag/ bjergart med en vis porøsitet f.eks. en sandsten, en "cap rock"/forsegling dvs. en impermeabel bjergart som f.eks. lersten og så en lukning dvs. en afgrænsning af reservoiret i geologiske strukturer som f.eks. antiklinaler/ domer, forkastnings blokke (forskudte jordlag) eller stratigrafiske afgrænsede lag. Olie, gas og saltvand findes i undergrunden i sådanne afgrænsede strukturer så som på dansk sokkel i Nordsøen, men i strukturer med potentiale for CO_2-lagring på land i Danmark er porevæsken oftest saltvand (også kaldet saline akviferer). Lageret kan være mere eller mindre effektivt afhængig af graden af porøsitet, permeabilitet og tryk som har betydning for flow i reservoiret. Lignende parametre er gældende for styrken af forseglingsbjergarten.

For at sikre at CO_2 forbliver i væskefase må det opbevares ved tryk større end dets kritiske tryk som er 73,9 bar. Det gennemsnitlige tryk i 800 m dybde er 80 bar så lagre dybere end det opfylder kriteriet. Typisk er lagre på 2-3 km dybde med et tryk på 200-300 bar og en temperatur på 60-100 grader Celsius. Dette giver en densitet af CO_2 på 0,5-0,8 g/cm^3. Sammenlignet med CO_2 gas, der har en densitet på 0,001 g/cm^3, er CO_2 på væske form altså tungere og fylder meget mindre hvilke betyder, at meget mere CO_2 kan opbevares i porerummet. Sammenlignet med vand med en densitet på 1 g/cm^3 er CO_2 lettere, hvilket betyder at det vil stige opad i reservoiret. Derfor er en impermeabel "cap rock"/forseglingsbjergarten vigtig.

Når CO_2 injiceres i et reservoir vil det presse formationsvandet væk og bevæge sig ind i porerummet på bjergarten og forme en "plume". I formationen/reservoiret vil ske en trykstigning, hvilket kan forårsage meget små forskydninger i undergrunden (mikrojordskælv). Hvis trykket er meget stort og ikke håndteret korrekt, kan det forårsage sprækker i forsegling og mulig lækage af CO_2.

I reservoiret er der 4 mekanismer der sammen bidrager til at "fange" og fastholde CO_2 i reservoiret (se Figur 5). En strukturel fælde, f.eks. en dome som tidligere diskuteret, men også kapillær fangst dvs. CO_2 bliver immobiliseret i porerummet, opløsning af CO_2 i formationsvandet samt reaktion mellem opløst CO_2 og bjergartsmineralerne, hvorved nye mineraler dannes [66].



Figur 5 Forskellige fangst mekanismer der immobiliserer CO_2 i jorden (Stephanie Flude, CC BY [67])

Udenlandske erfaringer danner et rimeligt fundament og sammenligningsgrundlag for danske lagringsforhold når der er tale om samme reservoirtype (sandsten, kalksten etc.), forseglingstype og struktur. Sammenligningen er skal dog altid laves med forbehold idet forhold såsom lithologi, dybde, kvalitet mv. kan have en indflydelse lokalt.

Mulige danske lagringsforhold findes diverse steder på land og vand, i diverse størrelser, dybder og lithologier. CO_2-lagrene Sleipner Vest og Snøhvit i Norge er eksempler på offshore CO_2 sandstenslagre som er sammenlignelige med nogle potentielle danske lagre. På Sleipner Vest foregår injektionen i et salint sandstensreservoir på 1.000m dybde, i Utsira fomationen der er 200-250m tyk.

Snøhvit er et salint sandstensreservoir i Tubasan formation på 2.550m dybde, reservoiret er 45-75m tyk. I Danmark er der erfaring med lagring af naturgas i underjordiske anlæg på land bl.a. i et akviferreservoir i Stenlille på Sjælland. Stenlille er en antiklinal struktur med et reservoir bestående af Triassisk Gassum Formation på 1.500 m dybde og en caprock af den Nedre Jurassiske Fjerritslev Formation.

CCS pilot projektet i Lacq bassinet i Frankrig er et eksempel på et kalkstensreservoir. Lagringen foregik i det udtømte Mano resevoir i Rousse feltet. Reservoiret er på 4.500m dybde, strukturen er Jurassisk.

I Danmark består en stor del af de kendte olie- og gasreservoirer af kalksten. Forståelsen af CO_2 lagring i kalksten i Danmark er ikke fuldt belyst. Kalkstens bjergarter er kendt for lav permeabilitet og det kan være vanskeligt at forudsige kvaliteten af reservoiret.

Flere Europæiske CCS studier [68] indikerer, at der er større volumen kapacitet i de danske sandstensreservoirer end i kalksten.

De potentielle danske CO_2 lagre omfatter sandstensreservoirer, som f.eks. INEOS's opererede offshore Nini og Siri felter (Projekt Greensand,1.500-2.000m dybde, 150-500 MT) [69], de store saline strukturer med triassisk Gassum formation reservoir Hanstholm (near-shore, antiklinal, ca. 1.000m dybde, kapacitet 2.753 MT) og reservoir Havnsø (onshore-near-shore, antiklinal, 1.500m dybde, kapacitet 926 MT) [70]).

GEUS gennemfører i 2021 en screeening af forskellige potentielt velegnede lagringsstrukturer. Undersøgelserne vil tjene som grundlag for at vælge en eller flere formationer, der skal undersøges nærmere.

I forslag til Danmarks Havplan, er Hanstholm og et større område ved den vestlige grænse i Nordsøen udpeget som udviklingszoner for CO_2-lagring [70].

Fordelen ved udtømte olie- og gas felter er, at det allerede er bevist at forseglingen virker over geologisk tid, og at der eksisterer en stor mængde data og viden om reservoiret. Yderligere er der et potentiale for brug af eksisterende infrastruktur. Saline reservoirer har historisk ikke haft den samme fokus, og her vil der skulle indsamles en større mængde nye data.

Særlig er lagerpotentialet typisk ikke er eftervist med en boring, hvilket er nødvendigt for at kunne bekræfte om lageret er velegnet og sikkert.

Forundersøgelser, etablering, drift og afvikling af CO_2 lagre

Herunder følger en gennemgang af erfaringer for de forskellige stadier for CO_2 lagre, herunder forskelle og ligheder for henholdsvis lagring på land, offshore eller nearshore. En scenarieoversigt med beskrivelse af de væsentligste aktiviteter under faserne forundersøgelser, anlæg og etablering, drift og afvikling fremgår af Tabel 6.

Tabel 6 Scenarieoversigt med beskrivelse af væsentligste aktiviteter

Scenarier		Forundersøgelser	Anlæg og etablering	Drift	Afvikling
På land	Nyt lager	Lager ikke bevist. Behov for seismik og brønddata	Injektionsboringer etableres med brøndhoved, pumpe , casing, filtre.	Reservoir overvågning, regelmæssig seismik	Plug & abandon brønd, forsat periodisk seismisk overvågning
	Tidligere gaslager	Lager bevist og godt kendskab til	Injektionsboringer og	Reservoir overvågning,	Plug & abandon brønd,

		reservoir egenskaber. Begrænset behov for ny data indsamling	etablering af permanente installationer	regelmæssig seismik	forsat periodisk seismisk overvågning
Offshore	Nyt lager	Lager ikke bevist. Behov for seismik og brønddata	Injektionsboringer og etablering af permanente installationer	Reservoir overvågning, regelmæssig seismik	Plug & abandon brønd, forsat periodisk seismik overvågning
	Tidligere O&G	Lager bevist og godt kendskab til reservoir egenskaber. Begrænset behov for ny dataindsamling.	Injektionsboringer	Reservoir overvågning, regelmæssig seismik	Plug & abandon brønd, forsat periodisk seismik overvågning
Nearshore	Nyt lager	Lager ikke bevist. Behov for seismik og brønddata	Injektionsboringer og etablering af permanente installationer	Reservoir overvågning, regelmæssig seismik	Plug & abandon brønd, forsat periodisk seismik overvågning

A.3.1 Forundersøgelser

Seismik

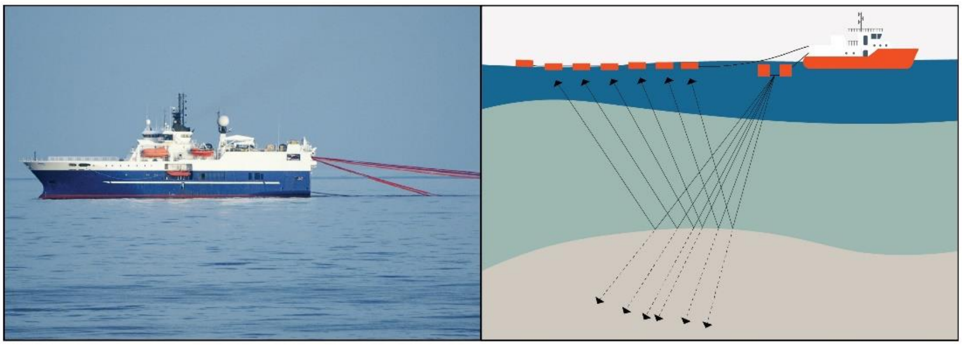
Indsamling af seismiske data og boringer er en fundamental del af forundersøgelserne for at forstå tilstedeværelsen, udbredelsen og kvaliteten af geologiske lagre. Den seismiske metode svarer til en stor-skala ultralydsskanning af undergrunden, hvormed det er muligt at identificere laggrænser og strukturer/forskydninger af sedimentære lag i undergrunden samt under visse forhold lithologi/ bjergarts type og tilstedeværelsen af gas, olie og vand. Seismiske undersøgelser kan udføres som 2D- eller 3D kortlægning. 2D kortlægningen består af en række udvalgte linjer, typisk planlagt i et grovmasket net, med afstande på 1-5+ km mellem de seismiske profiler. Dette giver en grundlæggende forståelse af undergrunden, men med større usikkerheder især for tynde lag, i forhold til dybden til toppen af lagene og for forkastninger. For med rimelig sikkerhed at kunne kortlægge laggrænser, strukturer, udbredelse af reservoiret, evt. interne forkastninger og sprækkesystemer, anvendes 3D seismik.

3D seismik er grundlæggende en 2D seismisk undersøgelse med større linjetæthed og større antal linjer, samt væsentligt forøget opløselighed vertikalt og horisontalt. En sådant datagrundlag kan muliggøre en detaljeret kortlægning af strukturen. Den forbedrede kortlægning gælder både en bedre opløselighed af tynde lag og til dybden til de enkelte lag samt en meget forbedret mulighed for kortlægning af forkastninger. For eftervisning af lithologien (typen af aflejring, f.eks. ler eller sand) og til undersøgelse af reservoir- og seglbjergarternes fysiske egenskaber kræves boring af en brønd.

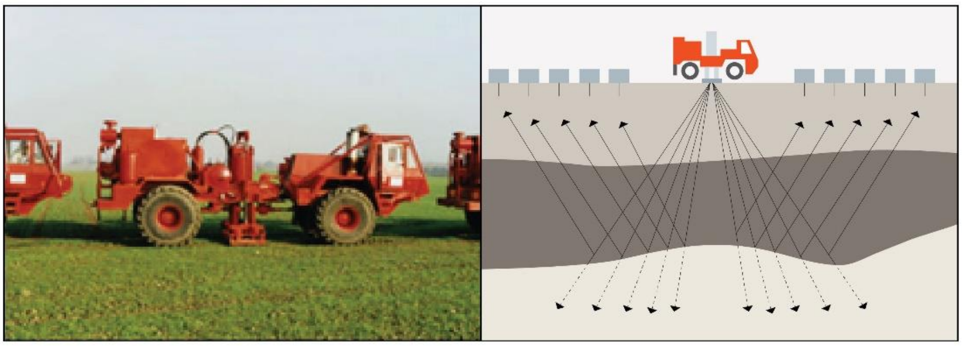
Der kræves forskelligt udstyr på land og på vand og det er særligt vanskeligt at dække kystområdet, hvor der er lavvandet og skal bruge en kombination af udstyr. Typisk indsamles og analyses 2D som et første skridt for at afdække om fundamentale elementer, en struktur, er til stede og derefter følges op med 3D data samt en brønd for detalje kortlægning. Her er det "cost" effektivt at tænke langsigtet med hensyn til at sikre at 3D kortlægningen kan fungere som et baseline for senere monitering af reservoiret.

Offshore foregår seismisk dataindsamling med specialbyggede seismiske skibe. Lydbølger sendes ned i jorden fra såkaldte "airguns"/luftkanoner som trækkes efter skibet. Disse signaler rammer jordens forskellige lag og reflekteres tilbage til havoverfladen, hvor de registres af trykfølsomme hydrofoner på et kabel som trækkes efter luftkanonerne. Dette er kendt som "streamer" seismik (Figur 6).

Til lands benyttes typisk vibratorlastbiler eller sprængladninger til at udsende lydbølger, som opsamles af geofoner på overfladen. Det er ofte mere besværligt at indsamle seismik på land end til havs pga. af flere obstruktioner. Landdata er ofte også mere påvirkelige af støj fra omgivelserne, hvilket kan betyde reduceret kvalitet af data.



Figur 6 Marin seismik data indsamling (Kilde GEUS efter Niels Ter-Borch, DONG Energy)



Figur 7 Land seismik dataindsamling (Kilde GEUS efter Niels Ter-Borch, DONG Energy)

Boringer

For at påvise type af bjergart og undersøge egenskaberne af reservoir og forsegling kræves boring af en brønd. Brønddata bestående af geofysiske logs, kerne data og tryk data er vigtige at indsamle. Geofysiske logs er vigtige for tolkning af geologi og kalibrering til seismik. Kernedata er vigtige for forståelsen af bl.a. bjergarts styrke og mekanik i forsegling samt for reservoir porøsitet og permeabilitet. Tryk data indsamles gennem brøndtest for at vurdere forseglingsstyrken i forhold til trykket i reservoiret samt permeabilitet/flow i reservoiret.

Offshore bores brønde fra borerigs specificeret efter vanddybde samt dybde og tryk i reservoiret (Figur 8). Disse er typisk flytbare og med beboelse for mandskabet. Nogle permanente produktionsplatforme er også udstyret til at bore brønde. På land er borerigge typisk noget mindre og kan flyttes med/på lastbiler.

Det er ikke en ufarlig proces at bore brønde, idet man har med tungt maskineri at gøre og under visse forhold brændbare hydrocarboner, kombineret med mulige overraskelser som f.eks. tryk, geologiske og vejrmæssige forhold. Det er dog en industri med stor erfaring og med et højt fokus på sikkerhed og på at processerne er optimeret og udføres sikkert.

Figur 8 Offshore Jack-up borerig (Kilde Maersk [71])

A.3.2 Anlæg og etablering

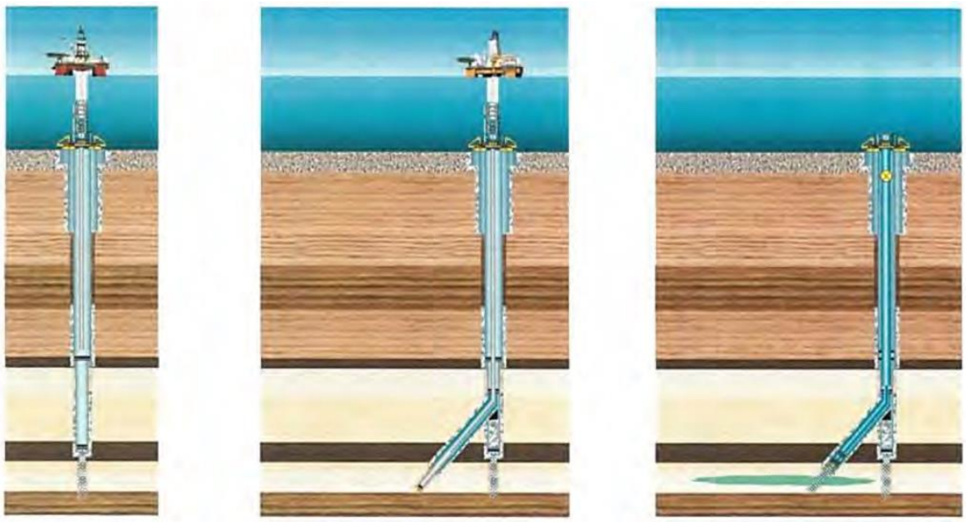
Injektion af CO_2 i undergrunden kræver som minimum én boring, hvor der bores igennem det valgte reservoir. En ny injektionsbrønd bores eller en eksisterende boring konverteres til CO_2-injektion.

På reservoirniveau udføres brønden med nødvendige filtre og det kan være nødvendigt at udføre injektionsforberedende test og oprensning f.eks. med kaliumklorid. Filtret giver adgang til reservoiret og sikrer, at uønskede partikler ikke injiceres og at reservoirets partikler ikke mobiliseres. Brønden fores (cases) for at sikre at CO_2 ikke kan undslippe ind til andre formationer. Der etableres et brøndhoved hhv. på jordoverfladen eller på havbunden. Det skal sikres at CO_2

injektionen udføres med et tryk og en temperatur der passer til forholdende i reservoiret og der placeres typisk anlæg enten i brønden eller ved brøndhovedet til tryksætning og opvarmning. Idet lækage kan ske direkte gennem brønden, bør den udstyres med instrumenter, der kan måle tryk- og temperaturændringer og derved overvåge evt. lækage. Det er også et krav i henhold til EU Direktiv 2009/31/EC [72].

CO_2 er korrosiv og studier konkluderer, at den vigtigste grund til at injektionsbrønde fejler skyldes, at der er brugt konstruktionsmaterialer som ikke er tilpasset CO_2, hvilket har ledt til korrosion af casing [68]. Ved brug af gamle brønde ved et eksisterende olie- og gasfelt, er det nødvendigt at renovere boringers opbygning så korrosion undgås. Det skal derfor dokumenteres og verificeres at brøndenes opbygning ikke udgør en risiko inden lageret tages i brug. Bekymringerne er typisk rettet mod cementen og eventuel reaktion med CO_2 [68].

På Sleipner Vest CO_2 projektet offshore Norge, sendes CO_2 ned i reservoiret via en dedikeret injektionsbrønd fra Sleipner A platformen. I Northern Lights projektet planlægges en undersøisk satellit, der forbindes med en rørledning til land mens monitorerings- og kontrolfunktioner planlægges udført fra Oseberg platformen (offshore [17]. Det planlægges endvidere at benytte forundersøgelsesbrønden til injektion efter re-design (Figur 9). På havbunden planlægges etablering af en undersøisk satellitfacilitet af størrelse 20,5x12,4x16 m.



Figur 9 Illustration af den planlagte udvikling af Northern Lights injektionsbrønden [17]. Venstre: Boring af forundersøgelses brønd i 2019/2020. Midt: Genåbning, re-design og færdiggørelse til injektion planlagt i 2022. Højre: Færdig injektionsbrønd i 2023/2024.

A.3.3 Drift

Driften af selve CO_2 lageret består af injektion af CO_2 og monitering af reservoiret. Et omfattende moniteringsprogram er nødvendigt for at demonstrere og dokumentere at den lagrede CO_2 forbliver i reservoiret. De fleste metoder er anvendelige både offshore og på land.

Undersøgelser, der udføres som en del af monitering skal kunne holdes op mod undersøgelser foretaget inden CO_2 injektion er påbegyndt. Dette refereres til som basisundersøgelser.

For selve reservoiret og forseglingsbjergarten udgør det 3D seismiske undersøgelser, der udføres for at kortlægge strukturen, den vigtigste baseline. Den kan benyttes til fremtidige, såkaldte 4D undersøgelser. 4D er ganske enkelt udførelse af to identiske 3D seismiske undersøgelser, forskudt i tid. Da udskiftningen af vand med CO_2 ændrer trykforholdene i reservoiret og dermed den seismiske respons, kan udbredelsen af CO_2 i reservoiret moniteres ved hjælp af forskellen i det seismiske signal med f.eks. 5-10 års mellemrum. Også andre metoder benyttes f.eks. mikro-gravimetriske undersøgelser, hvor ændringer af tyngdeforholdene måles, idet CO_2 er lettere end det saline vand.

Over 20 års erfaringer fra Sleipner CO_2 injektionsprojekt, verdens første industrielle offshore CCS projekt har netop vist, at gentagne seismiske undersøgelser (4D/ Timelapse) har været essentielle for at kunne overvåge CO_2 plumens indeslutning i reservoiret (Figur 10). Kombineret med gravimetriske data har det været muligt at kombinere CO_2 masseændringer og geometridata for derved at kunne estimere opløsning af CO_2 i vandet, hvilket er vigtigt for langtidsberegninger. Det er også vist, at tryk- og temperatursensorer ved brøndhoved og i reservoir er nødvendige for god kontrol af betingelser før og under injektion. Ved brug af disse overvågningsmetoder er det vist at CO_2 er forblevet sikkert nede i undergrunden [45]. Overvågningen følger krav jf. EU direktiv [72].

Mikro jordskælv (mikro-seismisitet) kan udløses ved injektion. Den geologiske risiko for betydende jordskælv er meget lille.

I Danmark er der erfaring med pumpning og lagring af naturgas i underjordiske anlæg på land bl.a. i et akviferreservoir i Stenlille på Sjælland. Der er 20 dybe brønde på Stenlille sitet, 14 injektions og produktions brønde og 6 overvågningsbrønde. Stenlille blev overvåget for seismiske events i perioden 2018-2020 og er ikke observeret seismiske events i den periode [73].

Monitering af CO_2's mulige indtrængning i grundvandet er også nødvendigt. Monitoreringen består typisk af et antal overvågningsboringer, hvorfra der kan indsamles flowdata og tages jævnlige vandprøver. Da CO_2 kan påvirke den kemiske sammensætning af grundvandet, bør der sammensættes et relevant laboratorieprogram. Data samles i en grundvandsmodel, der viser flowretning. I Stenlille gaslageret på Sjælland er grundvandet blevet overvåget via boringer siden anlægget blev anlagt i 1989. Kun et læk er blevet observeret, i 1995, relateret til et teknisk problem under injektion i St14 borigen [73].

Lækket blev hurtigt stoppet. Estimatet er at 5.000 m^3 gas blev tabt til lavere liggende geologiske formationer. En uge efter lækket blev der observeret forhøjede gaskoncentrationer i K1 vandboring, 250m fra St14 boringen. Der var ingen fri gas i vandprøven, og det blev konkluderet at alt gassen var opløst på det tidspunkt. Efterfølgende er koncentrationen af opløst gas faldet og i 2012 til under 1mg/l. Der blev også målt en stigning i metan i oktober 2009 i vandboring 558 sydvest for Nyrup. På den baggrund blev det konkluderet af traces af gas fra lækken i 1995 havde migreret ind og gennem et Paleocen sand lag til brønd 558. En begravet dal ved Nyrup har muligvis tilladt gassen at migrere til lavere dybder, hvor den blev gradvist opløst i grundvandet. Undersøgelserne viste også, at der var en meget lav pumpe rate i brønden som muliggjorde at detektere gas i vandet. Efter normal pumpe rate var etableret, kunne gas ikke længere måles [73].

Erfaringerne fra overvågningen af lageret ved Sleipner har givet input til fremtidige projekter. Læringen er at valget af overvågningsteknikker, hvornår og varigheden af overvågningsundersøgelser bør være projektspecifikke og risk baseret, samtidig med at den langvarige tidshorisont for CCS projekter også bør tages med i overvejelserne.

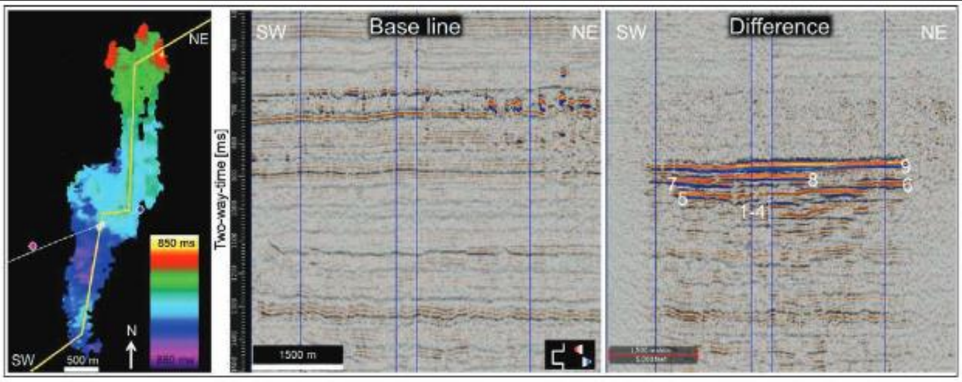


Figure 2: Left: Map of the two-way time interpretation of the uppermost layer of the CO_2 plume, interpreted on the 2013 seismic time-lapse processed data. The yellow line corresponds to the position of the vertical sections in the middle and right vertical plots, representing the 1994 baseline and the difference between the 2013 and 1994 seismic data, respectively. The white line on the map represents the injection well, with perforation interval indicated as parallel white lines, whereas the magenta circle represents the nearest exploration well.

Figur 10 Sleipner seismisk CO_2 overvågning [45].

A.3.4 Afvikling

I afviklingsfasen forsegles brøndene med en cement plug og overflade installationer fjernes ligesom for olie- og gasinstallationer. Energistyrelsens boreretningslinjer [44] angiver, hvordan brønde bør tilproppes, før de efterlades i henhold til godkendte procedurer. Brøndstedet skal genetableres i overensstemmelse med den oprindelige tilstand, og brøndstedet skal verificeres inden det efterlades.

Reservoiret overvåges dog forsat i afviklingsfasen vha. seismik. Når injektionen stoppes, falder trykket i reservoiret og derfor anses risikoen for brud på forseglingen og induceret seismisitet mindre i denne fase end i driftsfasen.

A.4 Transport af CO_2 på land og til havs

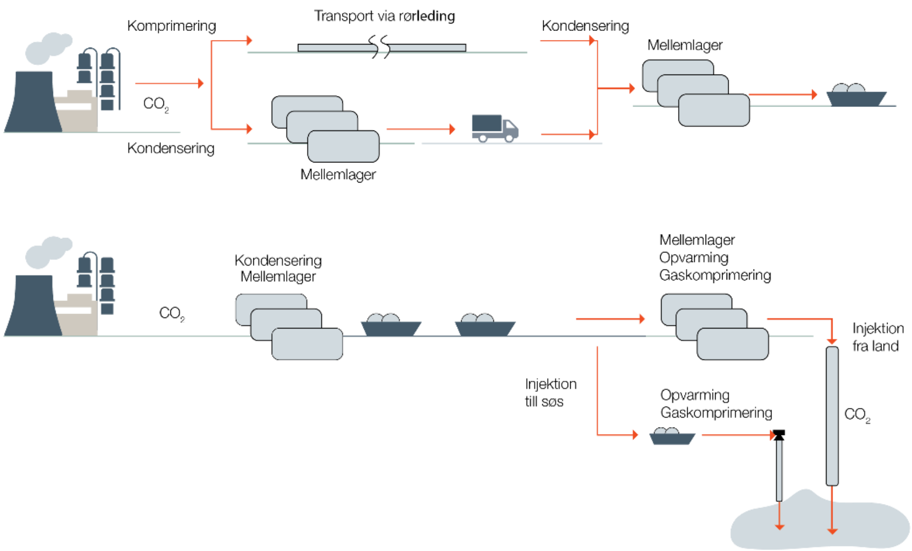
Transport af CO_2 kan ske som en komprimeret gas eller på væskeform. CO_2 transporteres som gas under højt tryk i rørledninger, samt ved mellemtryk og nedkølet som væske i f.eks. tanke. Rørledningstransport af CO_2 og andre gasser under tryk er en moden kommercielt tilgængelig teknologi.

Der transporteres globalt gas med tankskibe i LPG- og LNG-skibe (Liquified Petroleum/Natural Gas), hvor gassen ligesom CO_2 er hhv. under tryk eller nedkølet til væskeform. I Northern Lights projektet bygges i første fase to skibe til transport af flydende CO_2. Her er der specifikt tale om et tilpasset LPG skibsdesign med tilføjelse af et transportsystem til flydende CO_2 samt isolering. Hermed benyttes designs, som skibsværfter allerede kender.

Der findes mere end 3.000 km CO_2-rørledninger i Nordamerika, ca. 135 km flerfase rørledning til Snøhvit feltet i Norge og ca. 80-100 km CO_2-rørledning på land mellem Rotterdam og Amsterdam. Transport af gas i rørledninger eksisterer bl.a. som transportform af f.eks. naturgas i Danmark, mens CO_2 til fødevareindustrien i dag typisk transporteres til søs og på lastbil. Transporten til søs foregår med relativt små gastankskibe.

Transport af CO_2 som væske vil kræve etablering af et mellemlager samt opvarmning og komprimering forud for endelig lagring i undergrunden. Terminalerne vil typisk være designet med lastepumper, overførselsrørledninger, marine lastearme, måle- og genfordampningsanlæg til håndtering af CO_2 gas fra lagertanke osv. Ved destinationen til endelig lagring overføres CO_2 fra skib til injektionsfacilitet, hvor CO_2 opvarmes, komprimeres og injiceres.

Der er i det følgende anvendt informationer fra Energistyrelsens teknologikatalog for transport af energi og CO_2 [74].



Figur 11: Øverst: Transport af komprimeret CO_2 gas samt kondenseret CO_2. Nederst: Transport af CO_2 til injektion near-shore og offshore. En tredje mulighed er onshore og near-shore injicering fra en landbaseret facilitet, hvor kondensering ikke er nødvendig.

A.4.1 Forundersøgelser

Rørledning, lastbil, godstog og skib
Der skal udføres forundersøgelser af tracé og transportmidler i forhold til teknisk egnethed.

Forundersøgelserne forventes ikke at afvige fra forundersøgelser i forbindelse med transport af f.eks. naturgas og LNG.

A.4.2 Anlæg og etablering

Rørledning
Metoder for anlæg og etablering af rørledninger vil være tilsvarende, hvad der ses for rørledninger til transport af f.eks. naturgas og LNG.

Lastbil, godstog, skib
Ikke relevant

A.4.3 Drift

Transport i rørledninger

Rørledninger vil være relevant ifm. transport af store mængder CO_2, f.eks. fra store punktkilder til eksportterminaler samt videre til lagring i undergrunden. Standarden p.t. for transport over længere strækninger (fx. over 30 km) er tryk på 80 - 150 bar, hvilket sikrer en margin til trykfald samtidig med, at tykkelsen af røret kan holdes på et rimeligt niveau ift. materialeomkostninger. For kortere strækninger kan der anvendes tryk på 10 eller 30 bar alt efter om rørene er nedgravede. Der findes flere designstandarder for CO_2-rørledninger, se herunder DNV-RP-J202 og ISO 27913:2016. Der kan være mulighed for at benytte eksisterende naturgasrørledninger til CO_2-transport. Dette vil afhænge af, hvorvidt røret er i en dimension der passer og i det hele taget lever op til kravene CO_2 transport. Det vil skulle undersøges i de konkrete tilfælde.

Som tidligere nævnt sker der komprimering af CO_2 op til 150 bar samt tørring inden transport. CO_2-kompressoren styrer trykket ved indløbssiden af rørledningen, og ved afbrydelser af kompressoren benyttes ventiler for at afspærre mod rørledningen, så trykket fastholdes der. På land vil der også blive indsat ventiler langs rørledningen, så rørsegmenter kan isoleres ved lækage. Længden af hvert segment vil afhænge af en risikovurdering. F.eks. må der i tætbefolkede områder forventes kortere segmenter end i landdistrikter. Offshore vil der typisk ikke være afspærringsventiler mellem land og selve brøndhovedet.

Målestationer vil placeres ved kompressionsanlægget i indløbet eller i slutningen af røret. Er der tale om et egentligt netværk, kan det dog være relevant at etablere flere målestationer. Pumpestationer kan være relevante langs ruten for at overvinde tryktab, hvis trykket falder til under det minimale rørledningsdriftstryk (80 bar). Typisk kan dette være for hver 70-140 km. Pumperne placeres i dedikerede stationer / huse langs ruten. For offshore-rørledninger er dette ikke en mulighed og dimensionen skal derfor vælges, så det resulterende trykfald kan tolereres. I praksis betyder det, at diameteren øges med rørledningens længde ved fastholdt kapacitet.

Allerede eksisterende CO_2-rørledninger spænder vidt i kapacitet fra 0,06 til 27 mio. ton pr. år. I Danmark forventes behov for transport af 5-10 mio. ton pr. år, da dette vil dække mange af de største punktkilder. Det vil kræve en nærmere afdækning af de specifikke forhold i det enkelte projekt for at afgøre, om det er relevant med etablering af en rørledning ift. f.eks. lastbilstransport. Forventningen er, at kapaciteter under ca. 50-100 kton CO_2 pr. år vil blive kørt med lastbil.

Der forventes ikke nogen større miljøpåvirkning under almindelig drift, da der ikke vil være afgivelse af CO_2 fra rørledningen. Der kan ved vedligeholdelses- eller reparationsarbejde skulle foretages en kontrolleret nedblæsning af sektioner, hvorved en kort rørstrækning tømmes med udledning af en mindre mængde CO_2 til følge.

Under den daglige drift skal flow og tryk langs rørledningen overvåges kontinuerligt, herunder overføres aflæsningerne fra instrumenterne til et bemandet kontrolrum. Nedgravede rørledninger vil desuden normalt også være udstyret med katodisk beskyttelse ift. ekstern korrosion.

Rørledningen kan også være udstyret med interne inspektions- og rensefaciliteter i form af luger til en såkaldt "gris", der anvendes til overvågning af intern korrosion og tilsmudsning. Sammenholdt med naturgasrørledningerne forventes mindre intern rensning, da det er ren, tør CO_2-gas, der transporteres.

Hvor der er risiko for at CO_2 kan ophobes i farlige koncentrationer ved en læk (herunder CO_2-komprimerings- / pumpehuse, doseringshus, ventilhuller mv.), skal der være CO_2-detektorer og alarmer.

Flowet ind og ud af rørledningerne bestemmes ved måling som del af afregningen, når der er overføres mellem forskellige parter. Overvågning af CO_2-kvaliteten f.eks. fugtindhold, O_2-indhold og andre urenheder forventes at være et krav ved indløbet. Hermed sikres at CO_2-kvaliteten er tilstrækkelig ift. rørledningsmaterialer og produktspecifikationer.

For en CO_2-rørledning vil der være operationelle risici relateret til CO_2's fasEADfærd og belastningsudsving, f.eks. dannelse af væskefase eller tøris under pludselige trykfald, frysning af sikkerhedsventiler osv. Vedligeholdelsesstop med fuld trykaflastning skal udføres i et langsomt tempo for at forhindre frysning.

Sikkerheden ved naturgasrørledninger og relaterede installationer vurderes af Arbejdstilsynet og Sikkerhedsstyrelsen. Endnu vides ikke, hvilken myndighed der vil evaluere fremtidige CO_2-rørledninger, og hvilke sikkerhedskrav der i så fald vil være.

Skibstransport

Skibe vil være relevant for transport af større CO_2 over længere afstande. Dette kan f.eks. være transport fra store punktkilder til offshore lagringsfaciliteter eller havneterminaler. Skibene kan desuden sejle i rutefart mellem flere destinationer, hvor der indfanges mindre mængder CO_2. P.t. har de eksisterende skibe til CO_2 transport en forholdsvis lille lagerkapacitet på 1.000-2.000 m^3, hvilket må forventes at stige på sigt. Ved behov for etablering af ny infrastruktur til skibstransport, såsom kajpladser ved industrianlæg og ved udvidelse af eksisterende havnefaciliteter, kan der forventes en betydelig projektomkostning.

CO_2 transporteres i flydende form, og dette vil typisk ske ved mellemtryksbetingelser (15-18 bar og -27°C til -21°C). Der kan dog også anvendes lavtryksforhold (f.eks. 5-7 bar og ca. -50 ° C) eller højtryksforhold (40-50 bar og +5°C til +15°C). Forskellen ligger i CO_2 densiteten samt krav til trykbeholdere samt behovet for isolering af systemet.

Lastbilstransport

Transport af CO_2 på lastbil sker i flydende form svarende til skibstransportforholdene. Vejtransport af CO_2 vil være relevant for små til mellemstore mængder, f.eks. fra små punktkilder til CO_2-anvendelsesfaciliteter eller eksportterminaler. Typisk kapacitet for en lastbil er 25 – 30 ton CO_2.

CO_2-lastbiler fyldes fra mellemlagertankene. Terminalerne vil have dedikerede lastepladser med tankningsudstyr og gasreturledninger til stede. En lastbil med en kapacitet på 30 ton CO_2 kan fyldes med flydende CO_2 på ca. 45 min, hvilket også forventes som aflæsningstid på destinationen. Tankene på lastbilen er ikke udstyret med køling, men er i stedet isoleret. Derfor vil temperaturen og trykket stige en smule under transport. Flydende CO_2 er en kølevare og transporten bør derfor minimeres for at undgå for stort varmeoptag. Står tankbilen for længe, slippes CO_2 ud i en sikkerhedsventil på tanken. Transporten skal derfor planlægges.

Miljøpåvirkningen pga. lastbiltransport vil som for skibe hovedsageligt være i driftsfasen pga. det høje energibehov (brændstof) samt emissioner fra lastbilen.

Transport af CO_2 via lastbil foregår allerede i dag, og CO_2 sættevogne er derfor sikkerhedsmæssigt godkendt til vejtransport. Da kapaciteten af lastbilen er begrænset, vil en ulykke med resulterende læk af CO_2 have ret lokal effekt. Såfremt ruten involverer veje med områder, hvor luftudskiftningen er mindre, f.eks. tunneler, vil der dog være større risiko for at nå farlige niveauer af CO_2 ved en lækage.

Godstog

CO_2-transport via jernbanen er teknisk muligt, og kryogene godsvogne benyttes nogle steder i verden til at distribuere flydende CO_2 til industrielle brugere. P.t. er der i Danmark ganske få punktkilder med forbindelse til jernbanenettet, hvorfor det primært vil være relevant ifm. transport fra f.eks. en havnefacilitet til industri med anvendelse af CO_2. Det vil her være et springende punkt, at infrastrukturen allerede er på plads. Desuden er planlægningen af transporten anderledes end f.eks. benzin, da vognene ikke kan henstilles i længere tid pga. fordampning af flydende CO_2.

A.4.4 Afvikling

Rørledning
Afvikling af en CO_2 rørledning stiller ingen specifikke krav eller udfordringer ift. andre typiske rørledninger til gastransport.

Lastbil, godstog, skib
Afvikling vil være som for andre tilsvarende transporter.

Bilag B Opsummering af CCS erfaringer med sikkerhed, miljø og natur

CO_2 fangstanlæg inkl. konditionering	Sikkerhed/uheldsscenarier	Miljø	Natur
Forundersøgelser	Ingen særlige sikkerhedsmæssige forhold identificeret	Ingen særlige miljømæssige forhold identificeret	Ingen særlige naturmæssige forhold identificeret
Anlæg og etablering	Ingen særlige sikkerhedsmæssige forhold identificeret	Energiforbrug, ressourceforbrug, CO_2 footprint, støj, affald, emissioner til luft og vand – kan sammenlignes med andre industrianlæg	Arealinddragelse samt afledte effekter af udledninger og emissioner. Tilsvarende andre industrianlæg
Drift	Udslip/større lækage af CO_2, O_2, NH_3 eller aminer samt risiko relateret hertil	Energiforbrug, CO_2 footprint, kemikalieforbrug, eventuelle spild, og emission af aminer og nedbrydningsprodukter via luft, vand og affald Støj, kølevand (varmt) Chilled ammonia: Udledning af ammoniak Oxy fuel – mindre Nox udledning fra forbrænding	Afledte effekter af udledning og emissioner. Herudover tilsvarende andre industrianlæg
Afvikling	Ingen særlige sikkerhedsmæssige forhold identificeret	Tilsvarende andre industrianlæg	Tilsvarende andre industrianlæg
Mellemlager	Sikkerhed/uheldscenarier	Miljø	Natur
Forundersøgelser	Ingen særlige sikkerhedsmæssige forhold identificeret	Ingen særlige miljømæssige forhold identificeret	Ingen særlige naturmæssige forhold identificeret
Anlæg og etablering	Ingen særlige sikkerhedsmæssige forhold identificeret	Energiforbrug, CO_2 footprint, ressourceforbrug, eventuelle spild, støj - Tilsvarende andre industrielle lagerfaciliteter	Arealinddragelse samt afledte effekter af udledninger og emissioner.
Drift	Udslip af CO_2, samt risiko relateret hertil	Energiforbrug, CO_2 footprint, kemikalieforbrug, eventuel spild, støj, diffuse udledninger af CO_2 - Tilsvarende andre industrielle lagerfaciliteter	Arealinddragelse og eventuelle afledte effekter af udledning og emissioner
Afvikling	Ingen særlige sikkerhedsmæssige forhold identificeret	Tilsvarende andre industrielle lagerfaciliteter	Tilsvarende andre industrielle lagerfaciliteter
Geologisk lagring	Sikkerhed/uheldsscenarier	Miljø	Natur
Forundersøgelser	Risiko for ved boring at ramme lagre af kulbrinter, CO_2 og tilhørende risiko for blowout ved boring	Støj, emissioner, energiforbrug, udledning af kemikalier	Påvirkning af fisk og marine pattedyr af offshore seismiske undersøgelser Påvirkning af arealer og forstyrrelse af dyr ved onshore seismiske undersøgelser
Anlæg og etablering	Se forundersøgelser	Støj, emissioner, energiforbrug, ressourceforbrug, udledning af kemikalier	Fysisk forstyrrelse af havbund Tab af områder Ophobning af forurenende stoffer Forringet vandkvalitet
Drift	Risiko for udslip af CO_2 i havmiljø eller på land via revner mv.	Energiforbrug, udledning af kemikalier, diffus emission af CO_2	Forstyrrelse af kyst- og havfugle på grund af skibstrafik Mindre CO_2 lækage fra offshore lager har kun lokal påvirkning Risiko for CO_2 lækage til grundvand fra onshore lager
Afvikling inkl. monitorering	Risiko for udslip af CO_2 i havmiljø eller på land via revner mv	Støj, energiforbrug, udledning af kemikalier, affald	Tilsvarende anlæg og etablering samt forundersøgelser

CO_2 infrastruktur rør	Sikkerhed/uheldsscenarier	Miljø	Natur
Forundersøgelser	Ingen særlige sikkerhedsmæssige forhold identificeret	Ingen særlige miljømæssige forhold identificeret	Ingen særlige naturmæssige forhold identificeret
Anlæg og etablering	Ingen særlige sikkerhedsmæssige forhold identificeret	Støj, emissioner, energiforbrug, ressourceforbrug, eventuelle spild, emission under opstart af N2, CO_2, MEG - Tilsvarende påvirkning som ved etablering af f.eks. gasrør	Fysisk forstyrrelse af havbund/areal Tab /ændring af områder Forringet vandkvalitet / sediment
Drift	Udslip af CO_2, samt risiko relateret hertil	Energiforbrug, CO_2 footprint, kemikalieforbrug, eventuel spild, støj fra kompressorer, nedblæsning af CO_2. Tilsvarende drift af f.eks. Gasrør minus kulbrinter	Eventuelle afledte effekter af emissioner og udledning
Afvikling	Ingen særlige sikkerhedsmæssige forhold identificeret	Tilsvarende anlæg inkl. affald	Tilsvarende anlæg og etablering
Skib, lastbil, godstog	Sikkerhed/uheldsscenarier	Miljø	Natur
Forundersøgelser	Ingen særlige sikkerhedsmæssige forhold identificeret	Ingen særlige miljømæssige forhold identificeret	Ingen særlige naturmæssige forhold identificeret
Anlæg og etablering	Ingen særlige sikkerhedsmæssige forhold identificeret	Ingen særlige miljømæssige forhold identificeret	Ingen særlige naturmæssige forhold identificeret
Drift	Udslip af CO_2, samt risiko relateret hertil	Energiforbrug, CO_2 footprint, emissioner, støj	Tilsvarende anden mobil transport inkl. eventuelle afledte effekter af udledninger
Afvikling	Ingen særlige sikkerhedsmæssige forhold identificeret	na	na

Bilag C Longlist over litteratur gennemgået

A. C. Rohr, J. D. McDonald, D. Kracko, M. Doyle-Eisele, S. L. Shaw og E. M. Knipping, »Potential toxicological effects of amines used for CCS and their degradation processes,« Energy Procedia, årg. 37, pp. 759-768, 2013.

A. D. Nielsen, N. P. Christensen, P. Jørgensen og E. L. Lundsteen, »Catalogue of geological storage of CO2 in Denmark, Danish Energy Agency,« Rambøll, Copenhagen, 2021.

A. Hosa, M. Esentia, J. Stewart og S. Haszeldine, »Benchmarking worldwide CO2 saline aquifer injections,« March 2010. [Online]. Available: https://www.sccs.org.uk/images/expertise/reports/working-papers/wp-2010-03.pdf .

A. M. Omar, M. I. García-Ibáñez, A. Schaap, A. Oleynik, M. Esposito, E. Jeansson, S. Loucaides, H. Thomas og G. Alendal, »Detection and quantification of CO2 seepage in seawater using the stoichiometric Cseep method: Results from a recent subsea CO2 release experiment in the North Sea,« International Journal of Greenhouse Gas Control, årg. 108, nr. 103310, pp. 1-17, 2021.

A. McGillivray og J. Wilday, »Comparison of risks from carbon dioxide and natural gas pipelines,« Health and Safety Laboratory , 2009.

A.-K. Furre, O. Eiken, H. Alnes, J. N. Vevatne og A. F. Kier, »20 years of monitoring CO2-injection at Sleipner,« Elsevier, p. 3916 – 3926, 2017.

Aker Carbon Capture, »Experience-based approaches to lower carbon cement production - How the Brevik CCS project opens up new possibilities for other cement producers,« Aker Carbon Capture Norway AS, Lysaker, 2021.

ArkerSolutions, »Arker Solutions starts CCS test program at Preem Refinery in Sweden,« may 2020. [Online]. Available: https://www.akersolutions.com/news/news-archive/2020/aker-solutions-starts-ccs-test-program-at-preem-refinery-in-sweden/. [Senest hentet eller vist den August 2021].

Batres, Maya; Wang, Frances; Buck, Holly et al.; Environmental and climate justice and technological carbon removal, The Electricity Journal 34 (2021)

C. Bofeng og e. al, »China Status of CO2 Capture, Utilization and Storage (CCUS) 2019,« Center for Climate Change and Environmental Policy,Chinese Academy of Environmental Planning. 2020, 2019.

C. Oldenbrug og L. Pan, »Major CO2 blowouts from offshore wells are strongly attenuated in water deeper than 50 m,« Energy Geosciences Division - Lawrence Berkeley National Laboratory, 2019.

COWI, »Carbon Capture Technology Catalogue,« Kongens Lyngby, 2020.

Department of Energy & Climate Change, »Government Response to the House of Commons Environmental Audit Committee Report: Carbon Capture and Storage (CCS),« Crown Copyright, 2009.

Det Norske Veritas, »Design and operation of CO2 pipelines,« 2010.

E. Gjernes, L. I. Helgesen og Y. Maree, »Health and environmental impact of amine based post combustion CO_2 capture,« Energy Procedia, årg. 37, pp. 735-742, 2013.

ECHA (europa.eu), »Information om kemikalier - ECHA (europa.eu).,« 2021. [Online]. Available: https://echa.europa.eu/da/information-on-chemicals.

EIGA, »MINIMUM SPECIFICATIONS FOR FOOD GAS APPLICATIONS, Doc 126/20,« EUROPEAN INDUSTRIAL GASES ASSOCIATION, 2020.

Energistyrelsen og Energinet, »Technology data - Energy transport,« 2017.

Energistyrelsen og Energinet, »Technology Data - Industrial process heat,« 2020.

Energistyrelsen, »Guidelines for drilling, esploration,« 1988,2009.

Energistyrelsen, »Leverance 5.1: Miljø- og sikkerhedsaspekter i CCS-kæden,« København V, 2021.

Energistyrelsen, »Standard vilkår for forundersøgelser til havs,« 2017.

Energistyrelsen, »Technology Data - Energy transport,« 2020.

Equinor , »EL001 Northern Lights: Plan for utbygging, anlegg og drift - Del II: Konsekvensutredning - Oppsummering av høringsuttalelser og tilsvar til disse,« Equinor ASA, Stavanger, 2020.

Equinor, »EL001 Northern Lights - Mottak og permanent lagring af CO2. Plan for utbygg-ning, anlegg og drift. Del II - Konsekvensutredning.,« Oktober 2019.

Equinor, »Miljørisiko for EL001, Northern Lights, mottak og permanent lagring av CO2,« DNV GL AS Region Norway, 2019.

Equinor, »Northern Lights FEED Report,« Equinor, 2020.

Erhvervsministeriet, »Cirkulære om naturgaslager ved Stenlille,« Erhvervsministeriet , 1991.

Erhvervsministeriet, Cirkulære om naturgaslager ved Stenlille (Til Vestsjællands Amtskom-mune og Stenlille Kommune), 1991.

EU, »Directive 2009/31/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL, of 23 April 2009 on the geological storage of carbon dioxide and amending Council Directive 85/337/EEC, European Parliament and Council Directives 2000/60/EC, 2001/80/EC, 2004/35/EC, 2006,« 2009. [Online].

Europakommissionen og Det Europæiske Råd, »BILAG: Statusrapport om klimaindsatsen, herunder rapporten vedrørende situationen på kvotemarkedet og rapporten vedrørende ændring af direktiv 2009/31/EF om geologisk lagring af kuldioxid,« Den Europæiske Uni-ons Tidende, Årg. %1 af %2COM(2015) 576 final - Annex 2, pp. 1-8, 18 November 2015.

European Environment Agency, »Air pollution impacts from carbon cap-ture and storage (CCS),« 2011.

F. H. Hedlund, »Past explosive outbursts of entrapped carbon dioxide in salt mines provide a new perspective on the hazards of carbon dioxide,« Intelligent Systems and Deci-sion Making for Risk Analysis and Crisis Response, 2013.

F. H. Hedlund, »The extreme carbon dioxide outburst at the Menzengraben potash mine 7 July 1953,« Elsevier, 2011.

F. Harding, »D14 Outline Environmental Impact Assessment,« Pale Blue Dot, 2018.

F. Schilling, G. Borm, H. Würdemann, F. Möller, M. Kühn og C. GROUP, »Status Report on the First European on-shore CO2 Storage Site at Ketzin (Germany),« Elsevier, Energy Pro-cedia, p. 7, 2009.

G. Dautzenberg og T. Bruhn, »Environmental impacts from CCS technologies,« Institute for Advanced Sustainability Studies, Potsdam, 2013.

G. Peridas, »Permitting Carbon Capture and Storage Projects in California,« Lawrence Li-vermore National Laboratory, 2021.

Gassnova, »Developing longship - Key lessons learned,« 2020.

GESAMP, »High level review of a wide range of proposed marine geoengineering techniques,« INTERNATIONAL MARITIME ORGANIZATION, London, 2019.

Global CCS Institute, »CCS Targeting Climate Change - Brief for Policymakers,« Global Carbon Capture and Storage Institute Ltd, 2019.

Global CCS Institute, »Global CCS Institute facilities database,« 2021. [Online]. Available: https://co2re.co/ClimateChange.

Global CCS Institute, »Global status of CCS 2020,« 2020. [Online]. Available: https://www.globalccsinstitute.com/resources/global-status-report/. [Senest hentet eller vist den August 2021].

Global CCS Institute, »Unlocking private finance to support CCS investments,« Global Carbon Capture and Storage Institute Ltd, 2021.

Gov, CA., »California Air Resources Abroad - CSS,« 2021. [Online]. Available: https://ww2.arb.ca.gov/our-work/programs/carbon-capture-sequestration.

IEA, »20 Years of Carbon Capture and Storage - Accelerating Future Deployment,« International Energy Agency & OECD, Paris, 2020.

IEAGHG, »Environmental impacts of amine emissions during post combustion capture - Workshop 2010/11,« International Energy Agency Environmental Projects Ltd., Cheltenham, UK, 2010.

IEAGHG, »Evaluation of reclaimer sludge disposal from post combustion CO2 capture,« 2014.

IEAGHG, »The Process of Developing a Test Injection: Experience to Date and Best Practice,« International Energy Agency Environmental Projects Ltd., Cheltenham, UK, 2013.

IPCC, »IPCC Special Report on Carbon Dioxide Capture and Storage,« Cambridge University Press, 2005.

J. C. S. Long, »California's Energy Future: The View to 2050,« California Council on Science and Technology, Sacramento, California, 2021.

J. L. Lewicky, J. Birkholzer og C.-f. Tsang, »Natural and industrial analogues for leakage of CO_2 from storage reservoirs: identification of features, events, and processes and lessons learned,« Ernest Orlando Lawrence Berkeley National Laboratory , 2006.

J. L. M. Gibbins, »BAT Review for New-Build and Retrofit Post-Combustion Carbon Dioxide Capture Using Amine-Based Technologies for Power and CHP Plants Fuelled by Gas and Biomass as an Emerging Technology under the IED for the UK,,« 2021. [Online]. Available: https://ukccsrc.ac.uk/best-available-technology-bat-information-for-ccs/. [Senest hentet eller vist den august 2021].

J. M. Neff, »Fate and effects of water based drilling muds and cuttings in cold water environments.,« Review prepared for Shelle exploration an Production Company Houston Texas, 2010.

K. Fujita, Y. Kato, S. Saito, H. Kitamura, D. Muraoka, M. Udatsu, Y. Handa og K. Suzuki, »The effect of aerosol characteristics in coal- and biomass-fired flue gas on amine emissions,« 14th International Conference on Greenhouse Gas Control Technologies, GHGT-14, pp. 1-10, 2018.

K. M. Novak, N. Gaurina- Medimurec og L. Hrncevic, »Significance of enhanced oil recovery in CO2 emission reduction,« Sustainability, årg. 13, 2021.

K. Wallmann, M. Haeckel, P. Linke, L. Haffert og M. Schmidt, »Best Practice Guidance for Environmental Risk Assessment for offshore CO2 geological storage,« EU: ECO2 - Sub-seabed CO2 Storage: Impact on Marine Ecosystems, 2015.

KEFM, »Principaftale mellem regeringen (Socialdemokratiet), Venstre, Dansk Folkeparti, Radikale Venstre, Socialistisk Folkeparti, Enhedslisten, Det Konservative Folkeparti, Liberal Alliance og Alternativet om En køreplan for lagring af CO2,« Juni 2021 2021. [Online]. Available: https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&ved=2ahUKEwiQ3-Pky_HyAhWIz4sKHWjmD5sQFnoECAYQAQ&url=https%3A%2F%2Fkefm.dk%2Fmedia%2F637606718216961589%2FPrincipaftale%2520om%2520CO2-lagring.pdf&usg=AOvVaw1y6rm60I85JFg7tfo1qR0P . [Senest hentet eller vist den September 2021].

Klima-, Energi- og Forsyningsministeriet, »Bilag 4 - Udenlandske erfaringer,« København, 2020.

L. A. Kyhn, S. Wegeberg, D. Boertmann, P. Aastrup, J. Nymand og A. Mosbech, »Onshore Seismic Surveys in Greenland,« Aarhus University, DCE – Danish Centre for Environment and Energy, 2020.

L. Eilertsen, »Northern Lights. Konsekvensvurdering med hensyn på naturmiljø og biologisk mangfold på land,« Rådgivende Biologer AS, 2018.

L. I. Helgesen og E. Gjernes, »A way of qualifying Amine Based Capture Technologies with respect to Health and Environmental Properties,« Elsevier, Energy Procedia, p. 13, 2016.

Loria, Patricia and Bright, Matthew B.H, Lessons Captured from 50 years of CCS projects, The Electricity Journal 34 (2021)

M. Bui, C. S. Adjiman, A. Bardow, E. J. Anthony, A. Boston, S. Brown, P. S. Fenell, S. Fuss, A. Galindo, L. A. Hackett, J. P. Hallett, H. J. Herzog, G. Jackson, J. Kemper, S. Krevor, G. C. Maitland, M. Matuszewski, I. S. Metcalfe, C. Petit, G. Puxty, J. Reimer, D. M. Reiner, E. S. Rubin, S. A. Scott, N. Shah, B. Smit, J. P. M. Trusler, P. Webley, J. Wilcox og N. M. Dowell, »Carbon capture and storage (CCS): the way forward,« Energy and Environmental Science, årg. 11, pp. 1062-1176, 2018.

M. Hjorth, L. D. Kristensen, C. J. Murray, J. H. Andersen, S. Brooks og K. Sørensen, »Effects of oil and gas production on marine ecosystems and fish stocks in the Danish North Sea,« WSP Denmark, NIVA, Teknologisk Institut, 2021.

M. Myersa, C. White, B. Pejcic, A. Feitz, J. Roberts, Y.-Y. Oh, L. Xu, L. Ricard, K. Michael, A. Avijegon, P. K. Rachakonda, M. Woltering, A. Larcher, L. Stalker og A. Hortle, »CSIRO In-Situ Lab: A multi-pronged approach to surface gas and groundwater monitoring at geological CO2 storage sites,« Elseiver, Chemical Geology, p. 18, 2020.

M. N. Toftegaard, »OxyFuel combustion of coal and biomass,« 2011.

M. Roskilde, »Revurdering af miljøgodkendelser Stenlille gaslager,« Miljøministeriet, 2009.

Maersk Drilling, »MaerskDrilling,« [Online]. Available: https://www.maerskdrilling.com.

MAERSK OIL DBU, »Redegørelse for miljømæssige og sociale virkninger - ESIS-Tyra,« Rambøll, 2017.

Ministry of Petroleum and Energy, »Feasibility study for full-scale CCS in Norway,« Gassnova & Gassco, 2016.

NIPH, »Health effects of amines and derivatives associated with CO_2 capture: Nitrosamines and nitramines,« 2011. [Online]. Available: https://www.fhi.no/publ/2011/health-effects-of-amines-and-deriva/.

P. Deda, M. Elbertzhagen og M. Klussmann, »Light Pollution and the Impacts on Biodiversity, Species and their Habitats,« Everglades, nr. Secretariat of the Convention on the Conservation of Migratory Species of Wild Animals (UNEP-CMS), pp. 133-138, 2007.

P. Harper, »Assessment of the major hazard potential of carbon dioxide (CO2),« Health and Safety Executive, 2011.

P. J. Rew, P. Gallagher og D. M. Deaves, »Dispersion of subsea releases, review of prediction methodologies,« HSE BOOKS, HSE Executive- offshore technology report, 1995.

Project Greensand, »Project Greensand,« [Online]. Available: https://statics.teams.cdn.office.net/evergreen-assets/safelinks/1/atp-safelinks.html .

PTRC, »Aquistore: Leading the World in Deep Saline CO2 Geological Storage,« 2021. [Online]. Available: https://ptrc.ca/projects/co2-eor-and-storage/aquistore .

Rambøll, »CO2 fangst på danske affaldsenergianlæg,« København, 2020.

Rambøll, »LL. Torup Gaslager - Vedligeholdelsesprojekt,« 2016.

S. Benson og P. Cook, »Underground geological storage,« i Special Report on Carbon dioxide Capture and Storage, 2018, pp. 195-276.

S. E. Greenberg, »Illinois Basin Decatur Project,« 2015.

S. Flude. [Online]. Available: https://theconversation.com/carbon-capture-and-storage-has-stalled-needlessly-three-reasons-why-fears-of-co-leakage-are-overblown-130747.

S. Gant, M. Pursell, A. McGillivray, J. Wilday, M. Wardman og A. Newton, »Overview of carbon capture and storage (CCS) projects at HSE's Buxton Laboratory,« Health and Safety Executive, 2017.

Scottish Carbon Capture & Storage (SCCS), »Global CCS Map,« [Online]. Available: https://www.sccs.org.uk/expertise/global-ccs-map.

Scottish Environment Protection Agency, »Review of amine emissions from carbon capture (version 2.01),« Natural Scotland - Scottish Government, 2015.

Søfartsstyrelsen, »Danmarks havplan,« 2021. [Online]. Available: https://havplan.dk/da/page/info . [Senest hentet eller vist den 23 august 2021].

Søfartsstyrelsen, »Miljøvurdering af Danmarks Havplan,« COWI, 2021.

T. Bakke, J. Klungsøyr og S. Sanni, »Environmental impacts of produced water and drilling waste discharges from the Norwegian offshore petroleum industry,« Marine Environmental Research, årg. 92, pp. 154-169, 2013.

T. Dahl-Jensen, R. Jakobsen, T. B. Bech, C. M. Nielsen, C. N. Albers, P. H. Voss og T. B. Larsen, »Monitoring for seismological and geochemical groundwater effects of high-volume pumping of natural gas at the Stenlille underground gas storage facility, Denmark,« GEUS Bulletin, p. 8, 2021.

T. Lecomte, J. F. F. d. l. Fuente, F. Neuwahl, M. Canova, A. Pinasseau, I. Jankov, T. Brinkmann, S. Roudier og L. D. Sancho, »Best Available Techniques (BAT) Reference Document for Large Combustion Plants,« 2017.

T. Nguyen, M. Hilliard og G. Rochelle, »Volatility of aqueous amines in CO_2 capture,« Energy Procedia, årg. 4, pp. 1624-1630, 2011.

The Danish Hydrocarbon Research and Technology Centre, »CO2 storage in Danish Oil & Gas fields,« DTU, Kongens Lyngby, 2020.

Total, »Carbon capture and storage, The Lacq pilot - results and outlook,« 2013.

Total, »Carbon capture and storage, the Lacq pilot, project and injection period 2006-2013,« 2014.

UK Environmental Agency, »Guidance, Post-combustion carbon dioxide capture: best available techniques (BAT),« july 2021. [Online]. Available: https://www.gov.uk/guidance/post-combustion-carbon-dioxide-capture-best-available-techniques-bat#who-this-guidance-is-for . [Senest hentet eller vist den August 2021].

US National Energy Technology Laboratory; Overview of potential failure modes and effects associated with CO_2 injection and storage operations in saline formations; december 2020, DOE/NETL-2020/2634

US National Energy Technology Laboratory; Best practices manuals; https://www.netl.doe.gov/coal/carbon-storage/strategic-program-support/best-practices-manuals

US Office of Fossil Energy and Carbon Management, »Report of the Interagency task force on Carbon Capture and Storage,« 2010.

W. Leiss og D. Krewski, »Environmental scan and issue awareness: risk management challenges for CCS,« Int. J. Risk Assessment and Management, pp. 234-253, 2019.

ZEP, »CO2 Storage Safety in the North Sea: Implications of the CO2 Storage Directive - TWG Collaboration across the CCS Chain,« European Zero Emission Technology and Innovation Platform, 2019.

ZEP, »Future CCS Technologies,« European Zero Emission Technology and Innovation Platform, 2017.

Kontor/afdeling
Center for Systemanalyse

Punktkilder til CO_2 – potentialer for CCS og CCU

Dato
15-06-2021

Hovedkonklusioner

- I 2040 vurderes potentialet for CO_2-fangst fra punktkilder, under stor usikkerhed, at udgøre ca. 4,5-9 mio. ton CO_2, hvoraf ca. 3,5-6 mio. ton stammer fra biogene kilder. Dertil kommer et potentielt meget stort potentiale for CO_2-fangst fra atmosfæren (DAC).
- Hovedparten af potentialet (op mod ca. 6,5 mio. ton CO_2) i 2040 stammer fra punktkilder koncentreret i 5 klynger omkring København, Aarhus, Aalborg og i Sydjylland.
- Der kan forventes at være et betydeligt potentiale for fangst af CO_2 fra punktkilder i Danmark frem mod 2030 og 2040. Potentialet er følsomt over for en række faktorer, herunder særligt størrelsen på den enkelte punktkilde og fremtiden for de biomassefyrede anlæg i el- og fjernvarmesektoren.
- Teknologi til opsamling af CO_2 fra mindre punktkilder under 100.000 ton CO_2 per år kan blive afgørende for realisering af potentialet.
- Størstedelen af potentialet (ca. 6-8 mio. ton) vurderes at være forbundet med omkostninger til fangst (heri ikke indregnet omkostninger til transport, mellemlagring og lagring) under 800-1.000 kr./ton.

Behov for yderligere viden og teknologiudvikling

- Potentialet er følsomt over for størrelsen af de medregnede punktkilder, herunder økonomien i opsamling af CO_2 fra kilder under 100.000 ton per år. Disse kilder vurderes at ville kunne anvende standardiseret fangstteknologi, som er under anvendelse på biogasopgraderingsanlæg i dag. Der kan med fordel iværksættes undersøgelser i mulighederne for opsamling fra anlæg i denne størrelsesorden.
- Potentialet for punktkilder er af begrænset størrelse, sammenlignet med størrelsen af udledninger i andre sektorer. Der kan være behov for at øge

Energistyrelsen

Carsten Niebuhrs Gade 43
1577 København V

T: +45 3392 6700
E: ens@ens.dk

www.ens.dk

mængden af biogens kulstof fx gennem fremme af udviklingen af teknologi til opsamling af CO_2 fra atmosfæren.

Analysen

INDHOLD

Leverance 1.1 Punktkilder til CO_2 – potentialer for CCS og CCU 1

Hovedkonklusioner 1

Analysen 3

INDHOLD 3

Indledning 4

Formål med analysen 5

Opsamling af CO_2 fra punktkilder 5

Metode 6

Afgrænsning af potentialet 7

Relevante størrelser af punktkilder for opsamling 7

Opgørelse af punktkilder i Danmark 10

Perspektivering til andre punktkildeopgørelser 12

Sektorspecifikke overvejelser 15

Industri 15

Affaldsforbrænding 18

El- og fjernvarmeproduktion 20

Anlæg til opgradering af biogas 25

Opgørelse af potentialet efter omkostninger 27

Geografisk fordeling af punktkilder 28

Bilag 1 – Metode 40

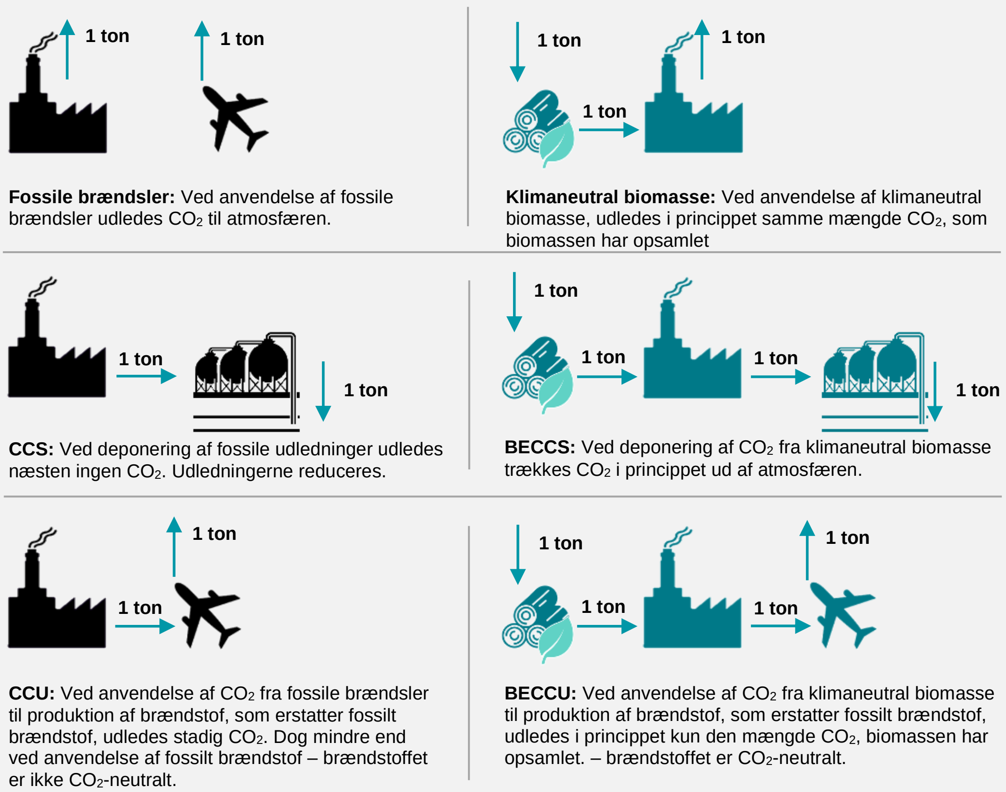
Afgrænsning af potentialet 41

Omkostninger til CO_2-fangst 41

Indledning

Teknologierne CCS (fangst og lagring af CO_2) og CCU (fangst og anvendelse af CO_2) afhænger begge af, at CO_2 opsamles, hvorefter det enten kan lagres geologisk eller anvendes til produktion af brændstoffer eller kemikalier. I det perspektiv kan CO_2 opfattes som en ressource, der er nødvendig, for at de givne teknologier (CCU og CCS) kan levere de nødvendige "klimatjenester". I tilfælde af CCU er tjenesten *fossilfrigørelse* gennem produktion af grønne ækvivalenter til nuværende fossile forbrug af brændstoffer eller kemikalier. I tilfælde af CCS lagres CO_2'en geologisk i undergrunden. Hvis kulstoffet stammer fra fossile brændsler eller lign., er CCS-tjenesten *nulemission.* Er der derimod tale om klimaneutral, biogen CO_2, eller CO_2 der stammer fra luften, er tjenesten *negative emissioner*. Dette illustreres i Figur 1 nedenfor. I denne sammenhæng er udledninger fra kemiske processer i industrien (altså ikke fra anvendelsen af brændsler) at regne for fossile, såfremt de kommer fra raffinaderiproduktion, mineralogiske processer eller lign. som fx cementproduktion, hvorimod udledninger fra biologiske processer i industrien som fx gæring er at regne for biogene.

Figur 1 - Principper for CO_2-udledninger i forskellige anvendelser



Potentialet for anvendelse af teknologierne afhænger derfor bl.a. af den mængde CO_2, der er til rådighed, og som det er teknisk muligt og økonomisk hensigtsmæssigt at opsamle.

Formål med analysen

Formålet med nærværende analyse er at opgøre de forventede udledninger fra punktkilder samt hvilken andel af dette potentiale, der vurderes at være tilgængeligt for opsamling og efterfølgende lagring eller anvendelse i 2025, 2030 og 2040. Frem mod 2030 og 2040, forventes der at være CO_2 til rådighed for fangst fra anlæg, som allerede eksisterer i dag og fra nyetableringer, som endnu ikke er kendte. Denne analyse beskæftiger sig med kendte anlæg samt reinvesteringer og nyetablerede anlæg i affaldsforbrændingssektoren, el- og fjernvarmesektoren og for biogasopgraderingsanlæg. Der er således ikke taget stilling til muligheden for etablering af nye store industrianlæg, kraftvarmeværker eller lign.

Opsamling af CO_2 fra punktkilder

Den bedst kendte teknologi til CO_2-fangst er aminbaseret røggasrensning, som ifølge Energistyrelsens teknologikatalog kan opsamle op mod 90-95 pct. af CO_2 i røggassen[1]. Med denne teknologi ledes røggassen fra fx et kraftvarmeværk gennem en reaktor hvor CO_2 "vaskes" ud af røggassen med en vandig amin-opløsning. Den nu CO_2-holdige væskestrøm varmes op i en anden reaktor, hvorved CO_2 frigives og kan renses og komprimeres, før den transporteres til deponering eller anvendelse. Denne type anlæg er komplicerede proceskemiske anlæg, som vurderes typisk at være underlagt skalaøkonomi (enhedsomkostningerne falder, jo større anlæg der kan etableres), ligesom den efterfølgende transport og lagring er. Dette giver et naturligt fokus på store punktkilder til CO_2. Det vurderes fx ikke at være rentabelt, at etablere CO_2-opsamling på fx gasfyr, lastbiler eller tilsvarende meget små, spredte kilder.

Store CO_2-punktkilder kan fx være fossile eller biomassefyrede kraftvarmeværker, affaldsforbrænding eller industrianlæg, der enten anvender brændsler til deres processer, eller hvor processen i sig selv udleder CO_2 (eksempelvis cementindustri). Der kan også være tale om mindre kilder som fjernvarmeværker, mindre industrianlæg, off-shore anlæg eller anlæg til opgradering af biogas, hvor CO_2'en allerede i dag separeres fra biogassen og udledes til atmosfæren, inden biogassen kan fødes ind i naturgasnettet. De ovennævnte typer af anlæg fordeler sig på fem sektorer, som det fremgår nedenfor.

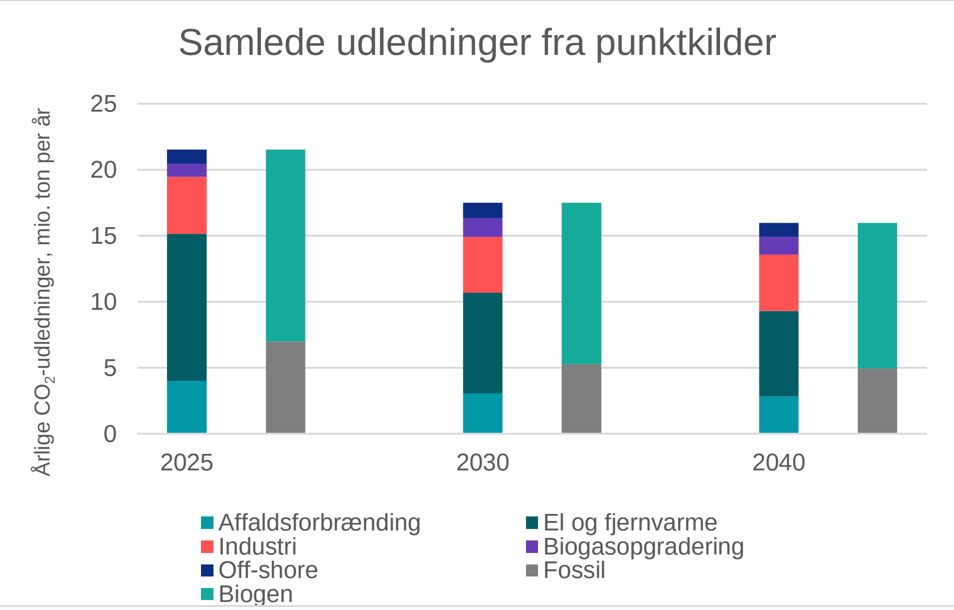
Ifølge Energistyrelsens seneste *Klimastatus og -fremskrivning 2021* (KF21) forventes der i 2025 at være i alt ca. 21,5 mio. ton CO_2-udledninger pr. år fra de pågældende sektorer, faldende til ca. 17,5 mio. ton i 2030. Herefter vurderes udledningerne af falde yderligere til ca. 16 mio. ton i 2040.[2] Disse tal inkluderer biogene udledninger, som ikke tælles med i det nationale CO_2-regnskab ift. opfyldelse af 70-pct. målsætningen. Biogene kilder er dog relevante i forbindelse

---

[1] Energistyrelsens teknologikatalog for procesvarme og carbon capture, https://ens.dk/service/fremskrivninger-analyser-modeller/teknologikataloger/teknologikatalog-procesvarme-og-carbon

[2] Fremskrivningsmetoden beskrives nærmere i afsnittet "Metode" og i Bilag 1.

med både deponering og anvendelse af CO_2 som beskrevet ovenfor, og de opgøres derfor også i dette notat. Den langsigtede udvikling for alle punktkildernes CO_2-udledninger er dog behæftet med betydelig usikkerhed.



Figur 2 CO_2-udledninger inkl. fossile udledninger, biogene udledninger og procesudledninger fra sektorer med punktkilder i Danmark. Affaldsforbrænding, el- og fjernvarmeproduktion samt industri indeholder både fossile og biogene udledninger. Industrisektoren indeholder tillige procesudledninger. Tallene kan ikke sammenlignes med opgørelser af udledninger i KF21, jf. Bilag 1, eller opgørelser af de nationale udledninger eller mankoen ift. målopfyldelse i 2030, da biogene udledninger ikke indgår i opgørelsen ift. 70 pct.-målet. Kilde: Energistyrelsen

Metode

Opgørelserne i dette notat tager udgangspunkt i Energistyrelsens Klimastatus og – Fremskrivning 2021 (herefter KF21), som indeholder en *frozen policy*-fremskrivning af udviklingen i det danske energisystem frem til 2030 – det som tidligere var kendt som Energistyrelsens basisfremskrivning. Sektorerne affaldsforbrænding, el- og fjernvarmeproduktion samt off-shore fremskrives direkte i KF21, mens industri og biogasopgradering er fremskrevet på baggrund af aggregerede forløb fra KF21. Perioden mellem 2030 og 2040 indgår ikke i KF, men er i stedet vurderet ud fra tendenserne i KF21 og fremskrevet frem til 2040. Dette beskrives nærmere i *Bilag 1 – Metode*.

Opgørelsen tager udgangspunkt i udledninger fra alle kendte punktkilder i de pågældende sektorer, og er aggregeret efter sektorer på en anden måde end i KF21. Hertil kommer, at rene kondensværker (elproduktion uden samtidig varmeproduktion) ikke er medtaget i denne opgørelse, da disse anlæg kun har få årlige driftstimer og derfor ikke er relevante for CO_2-fangst.

Afgrænsning af potentialet

Fra fremskrivningen beskrevet ovenfor opnås de samlede udledninger for de forskellige sektorer i 2025, 2030 og 2040. Ikke alle disse udledninger vil kunne opsamles i praksis. Derfor afgrænses potentialet på følgende måde:

Først og fremmest kan typiske aminanlæg til CO_2-fangst i dag maksimalt opsamle omkring 90 pct. af CO_2-indholdet i røggas. Derfor nedskrives potentialerne for alle sektorer på nær biogasopgradering[3] med 10 pct. Herefter baseres det øvre skøn for fangstpotentialet ift. punktkildernes størrelse for hver sektor, og det nedre skøn beror på en følsomhedsvurdering for de enkelte sektorer. Dette beskrives løbende i resten af notatet.

Off-shore medregnes ikke

Offshore-sektoren dækker over olie- og gasudvinding i Nordsøen, og sektoren tegner sig samlet set for godt 1 mio. ton i 2025. Emissionerne stammer fra en række mindre kilder, som umiddelbart vurderes vanskelige og omkostningstunge at indsamle, samt anvende/deponere. Det kan dog ikke afvises, at udledningerne fra sektoren vil kunne opsamles og deponeres i undergrunden under Nordsøen. Omvendt, vurderes hovedparten af udledningerne at stamme fra energiproduktion, som har et vist elektrificeringspotentiale. Dette analyseres i den igangværende elektrificeringsanalyse jf. Nordsøaftalen fra december 2020. Endelig vurderes olie- og gasaktiviteterne at blive udfaset frem mod 2050. Det er derfor uafklaret hvorvidt CO_2 udledninger fra offshore-sektoren vil være egnede til indfangning af CO_2, og sektorens udledninger er derfor ikke behandlet nærmere i denne analyse.

Relevante størrelser af punktkilder for opsamling

Energistyrelsens teknologikatalog viser, at der må forventes at være en vis storskalafordel forbundet med CCS-anlæg[4]. Dette gælder både selve anlægget til fangst og efterbehandling af CO_2 men også for transport og mellemlagring. Dermed må det – alt andet lige – forventes at være billigere at opsamle, transportere og lagre et ton CO_2 fra én stor punktkilde placeret tæt på andre punktkilder og tæt på lageret end fra mange små kilder placeret langt fra hinanden.

Dette giver et naturligt fokus på store punktkilder og punktkilder i klynger tæt på havne som oplagte kandidater til tidlige indsatser. Samtidig vurderes det for

[3] Udledningerne fra biogasanlæg er allerede separeret fra røggassen og kan anvendes efter rensning og tryksætning. De opgjorte udledninger skal derfor ikke gennem et nyt aminanlæg først og mister derfor ikke de 10 pct.

[4] Kilde: Energistyrelsens teknologikatalog for procesvarme og carbon capture, https://ens.dk/service/fremskrivninger-analyser-modeller/teknologikataloger/teknologikatalog-procesvarme-og-carbon.

nuværende, at der er CO_2-kilder, som er for små til, at det kan betale sig at opsamle CO_2 fra dem.

Boks 1 Opgradering af biogas – eksisterende CO_2-fangst

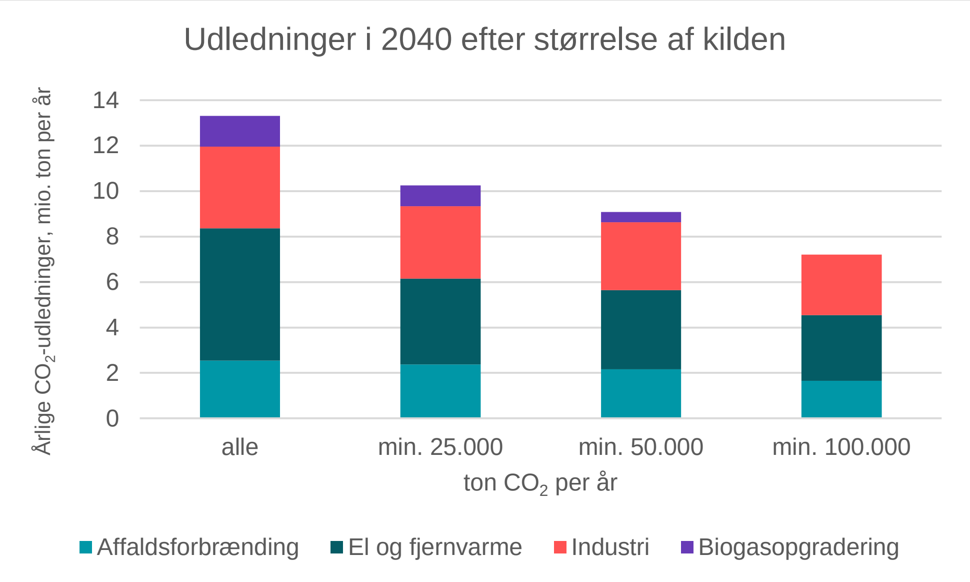
Der eksisterer i dag mere end 50 anlæg, der fanger CO_2 i forbindelse med opgradering af biogas i Danmark. I disse processer separeres CO_2-indholdet (ca. 30-40 pct.) i den rå biogas og udledes til atmosfæren, inden den opgraderede (CO_2-fri) biogas indfødes i naturgasnettet. Disse anlæg findes i drift i størrelser mellem 1.000 og 50.000 ton CO_2 per år. Disse anlæg vil kunne blive opfattet som værende for små til, at det kan betale sig at etablere fangstanlæg til at opsamle CO_2'en. Punktkildeopgørelsen i regeringens *Klimaprogram 2020* arbejder med en minimumsstørrelse for punktkilder i affaldssektoren, fjernvarmesektoren og industrien på 50.000 ton per år. Da CO_2'en allerede separeres fra biogassen, vurderes disse anlæg alligevel at være relevante som punktkilder til CO_2. Da CO_2'en fra biogasanlæg ikke er behæftet med bæredygtighedsproblematikker i samme omfang som andre biogene kilder, vurderes CO_2'en fra biogasanlæg desuden at kunne have en merværdi ift. CCU.

Separering af CO_2 i forbindelse med opgradering af biogas, jf. boks 1 foregår i mindre modulære anlæg i modsætning til de store specialbyggede anlæg, der kan anvendes på fx centrale kraftvarmeværker. Det vurderes, at masseproduktion og standardisering af denne type mindre CO_2-separeringsanlæg potentielt muliggør, at anlægsomkostningerne for denne type anlæg kan være lavere end for store anlæg. Der er indikationer på, at dette kan medføre lavere fangstomkostninger for små anlæg, og der er eksempler på bl.a. affaldsforbrændingsanlæg, der er i gang med at etablere CO_2-fangst svarende til ca. 50.000 ton per år baseret på teknologien fra biogasopgradering.

De ovenstående overvejelser kunne tale for at anvende en lavere grænse for punktkilder i forbindelse med potentialeopgørelsen. I tillæg til størrelsen (CO_2-udledning per år), spiller en række andre faktorer dog ind på økonomien i fangst af CO_2:

- Størrelse af punktkilden (ton per år)
- Transportafstand til mellemlager og udskibning/lagring/anvendelse
- Afstand til andre punktkilder/placering i klynger
- Etableringsomkostninger (CAPEX) og dermed også den forventede forrentning (WACC)
- Årlig driftstid for anlægget (antal fuldlasttimer), som definerer CAPEX andel af omkostningen per opsamlet ton CO_2
- Placering ift. et fjernvarmenet af en vis størrelse, der muliggør udnyttelse af overskudsvarme fra fangstprocessen, hvilket kan give et bidrag til økonomien.

Der er ikke udarbejdet en konkret analyse af samspillet af disse faktorer for de hundredevis af mindre punktkilder i Danmark, da dette i en vis udstrækning vil kræve individuelle konkrete vurderinger. I Figur 3 vises dog en opgørelse af potentialet i 2040 baseret på forskellige afskæringer i størrelse.



Figur 3 Opgørelse af udledninger i 2040 afhængig af størrelsen på kilderne, der indgår. Fremtidige biogasopgraderingsanlæg er antaget at have størrelser over 50.000 ton per år.

Figuren viser, at det samlede potentiale i vid udstrækning afhænger af, hvor små punktkilder, der medregnes. Opgørelsen viser yderligere en række karakteristika ved store og små punktkilder og afhængighed af forskellige sektorer.

De største punktkilder ligger generelt i byer ved vandet

De største punktkilder i landet findes i affaldssektoren, industrien og de store kraftvarmeværker. Heraf ligger stort set alle de største punktkilder i eller tæt ved de fem største byer i landet, som alle er havnebyer. Undtagelser herfor er tre af de ti største affaldsforbrændingsanlæg i 2025 (Maabjergværket i Holstebro, Vestforbrænding i Glostrup og ARGO i Roskilde) og to af de ti største udledere i el- og fjernvarmesektoren (Herningværket og Randers Kraftvarmeværk). Dermed ligger hovedparten af de store udledere og dermed hovedparten af potentialet i klynger omkring de store byer, hvor koncentrationen af store kilder forventes at kunne bidrage positivt til økonomien i transport, mellemlagring samt deponi/anvendelse. Dette taler for at basere opgørelsen primært på de største punktkilder. Små og mellemstore udledere kan dog blive særligt interessante, hvis de ligger tæt på større klynger eller kan organiseres i egne klynger, eller hvis de ligger i nærheden af anden industri eller lign., som kan tænkes at anvende opsamlet CO_2. Den geografiske fordeling af punktkilderne behandles nærmere i slutningen af dette notat.

Store punktkilder ligger i store fjernvarmenet

Placering i store fjernvarmenet muliggør potentielt udnyttelse af overskudsvarme fra fangstprocessen. Der er behov for fjernvarmenet af en vis størrelse, for at sikre, at disse fleksibelt kan aftage de relativt store mængder overskudsvarme, der potentielt kan være til rådighed fra fangstanlæggene. Dette vil være størst til fordel for store punktkilder nær store byer sammenlignet med mindre punktkilder, da de store kilder alt andet lige vurderes at ville have nemmere ved at afsætte overskudsvarmen og herved opnår et positivt bidrag til økonomien i projektet.

Industrien har typisk højere forrentningskrav end forsyningssektoren

CO_2-fangst er forbundet med store initialomkostninger til ombygning og etablering af nye anlæg, og de aktører, der skal etablere anlæggene, må forventes at have visse forrentningskrav til investeringerne. Disse krav kan forventes at være højere end de relevante sektorers normale forrentningskrav (WACC), da der i nogen grad er tale om ny teknologi og nye markeder, hvilket øger investeringernes risici. De fleste industrivirksomheder arbejder desuden med interne forrentningskrav, som er markant højere end de kendes fra fx forsyningssektorerne. Dette kan potentielt betyde, at særligt industrisektoren kan finde investeringer i CO_2-opsamling uinteressante, også set i relation til, at energi og miljø sjældent er en del af virksomhedens hovedforretning. Dette taler for, at anlægge en højere minimumsgrænse for industrisektoren i forbindelse med opgørelsen.

Opsamling

Baseret på ovenstående, vurderes punktkilder over 50.000 ton CO_2/år i industrien, affaldsforbrænding samt el- og fjernvarmesektoren relevante for opsamling i tillæg til alle biogasopgraderingsanlæg, at være relevante for opsamling og efterfølgende anvendelse eller deponering. Dette uddybes yderligere i beskrivelserne for de enkelte sektorer nedenfor.

Opgørelse af punktkilder i Danmark

I det følgende redegøres for CO_2 punktkilder i Danmark, herunder mængden af CO_2-udledning frem mod 2025, 2030 og 2040, typer af punktkilder mv. for de fire sektorer affaldsforbrænding, industri, el og fjernvarme samt biogasopgradering.

Der er forskel på punktkilderne i de fire sektorer, både i forhold til CO_2-koncentration i røggassen, antallet af årlige driftstimer, økonomiske forhold og regulering omkring de pågældende aktører, placering og i forhold til usikkerheden om, hvorvidt kilderne er tilgængelige og velegnede til indfangning af CO_2 i fremtiden. Baseret herpå vurderes det, at indfangningspotentialet fra punktkilder i 2040 er ca. 4,5-9 mio. ton pr. år. Dette kunne fordele sig på sektorerne som angivet nedenfor. Heraf forventes op til ca. 3 mio. ton at stamme fra fossile brændsler og procesudledninger i industrien og en mindre mængde fossilt forbrændingsaffald, mens op mod ca. 6 mio. ton forventes at stamme fra biogene kilder.

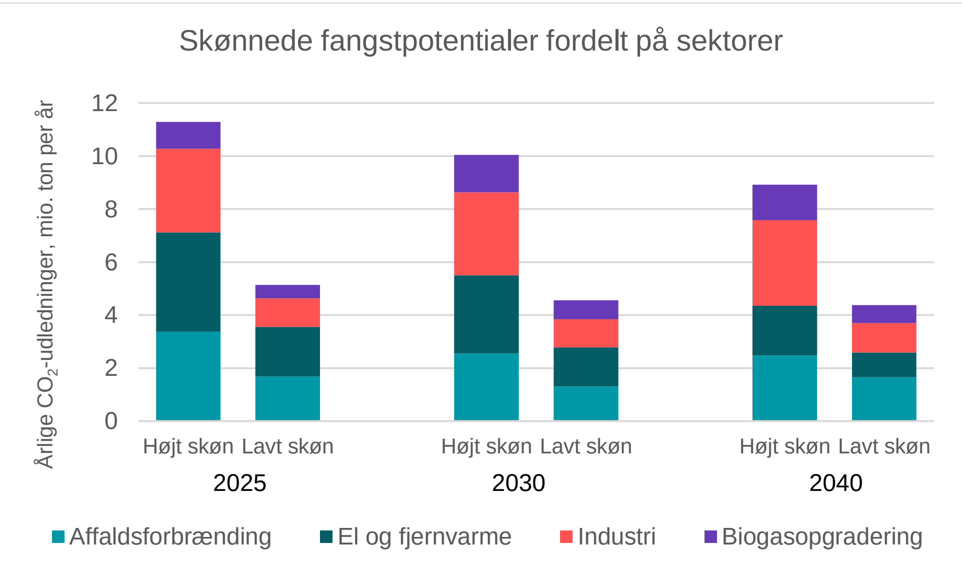
Det estimeres, at nedenstående udledninger vil være teknisk tilgængelige til indfangning i 2040 for de forskellige sektorer. Vurderingerne, der ligger til grund for de enkelte potentialeskøn gennemgås efterfølgende.

- **Affaldsforbrænding:** Ca. 1,5-2,5 mio. ton CO_2 pr. år fra anlæg over 50.000 ton per år. Heraf vurderes knap 1 mio. tons at kunne komme fra de tre største affaldsværker i Storkøbenhavn.

- **El- og fjernvarmeproduktion:** Ca. 1-2 mio. tons CO_2 pr. år fra anlæg over 50.000 tons per år med driftstider over 2.500 fuldlasttimer per år, hvoraf det største centrale biomassekraftvarmeværk, Amagerværkets Blok 4 forventes at udlede op mod 1 mio. tons alene.

- **Industri:** Ca. 1-3 mio. tons CO_2 pr. år, som for det høje skøn svarer til udledningerne fra Aalborg Portland, såfremt de erstatter deres forbrug af petrokoks med ledningsgas og fra raffinaderierne i Kalundborg og Fredericia samt øvrige industrielle udledere over 50.000 ton per år.

- **Biogasopgradering:** ca. 0,7-1,3 mio. tons CO_2 pr. år, spredt over mange (>50) mindre punktkilder. Biogasanlæggende medtages, da CO_2 allerede separeres i processen til biogasopgradering.



Figur 4 Øvre og nedre skøn over opsamlingspotentialer fordelt på sektorer frem til 2040. Det er behæftet med usikkerhed, hvorvidt punktkilderne vil være til stede i 2030 og 2040, samt hvor meget driftstid – og dermed udledninger – de enkelte anlæg har på sigt.
Kilde: Energistyrelsen

Perspektivering til andre punktkildeopgørelser

Figur 4 viser Energistyrelsens skøn for fangstpotentialerne i denne opgørelse. Spændene i de enkelte år udgør samlet set ca. 4,5-10 mio. ton CO_2 per år i 2030 og ca. 4,5-9 mio. ton CO_2 per år i 2040. Tabel 1 viser en sammenligning med skøn fra andre opgørelser.

Som det fremgår udgør nærværende opgørelse en mindre nedjustering ift. potentialeopgørelsen i Klimaprogram 2020. Årsagen til dette skal findes i flere modsatrettede udviklinger: Den mere indgående behandling af mindre punktkilder samt den opjusterede prognose for biogasopgradering trækker opad, mens sænkningen i forventede udledninger fra særligt affaldsforbrænding som følge af *Klimaplan for en grøn affaldssektor og cirkulær økonomi* og en mere indgående behandling af biomassekraftvarme trækker nedad.

Tabel 1 Sammenligning af opgørelser af fangstpotentiale.

Opgørelse	Potentialeskøn, mio. ton CO_2 per år 2030 Total	Heraf fossil	2040 Total	Heraf fossil
Denne analyse	4,5 - 10	1 – 3	4,5 – 9	0,5 – 3
Klimaprogram 2020	5 - 10	-	5 - 10	-
Dansk Energi, 2021	6,9	1,8	6,3	1,8
DØRS, 2021	3,5 - 6,5	0,5 - 1	-	-
Klimarådet, 2020	4,5	-	7,5 [a]	-

Noter:
[a]: Klimarådets opgørelse indeholder ikke et potentiale for 2040, men et samlet langsigtet potentiale, her anført i kolonnen for 2040.

Potentialet ligger endvidere lidt højere end potentialeopgørelserne fra Dansk Energi (DE), 2021[5], De Økonomiske Råd (DØRS), 2021[6] og Klimarådet, 2020[7] jf. tabellen. Opgørelserne fra DE og DØRS udgør økonomiske potentialer, der på baggrund af en række antagelser identificerer en andel af de samlede udledninger som egnede til opsamling, givet en bestemt betalingsvillighed. Begge opgørelser medregner kun i begrænset omfang mulighederne for billig opsamling fra små punktkilder baseret på modulær teknologi fra biogasopgradering, og opgørelsen fra DØRS medregner ikke potentialerne for opsamling fra biogas. Opgørelsen fra Klimarådet er en teknisk opgørelse baseret på økonomiske overvejelser, som kun medregner én punktudleder fra el- og fjernvarmesektoren. Klimarådet angiver i øvrigt ikke et

[5] Potentialet for CO2-fangst i Danmark til den grønne omstilling, Dansk Energi, 2021, https://www.danskenergi.dk/udgivelser/potentialet-co2-fangst-danmark-til-groenne-omstilling
[6] Økonomi og Miljø 2020, Kapitel I: Dansk klimapolitik frem mod 2030, Det Økonomiske Råds Sekretariat, https://dors.dk/vismandsrapporter/oekonomi-miljoe-2020
[7] Kendte veje og nye spor til 70 procents reduktion, Klimarådet, 2020, https://klimaraadet.dk/da/rapporter/kendte-veje-og-nye-spor-til-70-procents-reduktion

potentiale i 2040, men opererer med et samlet potentiale (angivet i kolonnen for 2040 i tabellen), hvoraf en andel vurderes at kunne realiseres i 2030. Nærværende opgørelse forholder sig ikke til, hvad der vil kunne realiseres inden 2030 eller 2040.

Sammenligningen peger også på de centrale usikkerheder i nærværende opgørelse:

- Særligt i el- og fjernvarmesektoren består en stor del af det opgjorte potentiale af mindre og mellemstore kilder. De økonomiske perspektiver i opsamling af CO_2 fra disse kilder vurderes at afhænge af, at teknologien fra biogasanlæg kan udbredes til fjernvarmesektoren med lavere omkostninger til følge.

  En væsentlig udfordring ved de små punktkilder – givet at opsamlingsteknologien er billig nok – er transportafstande. Her henledes opmærksomheden på det samlede potentiale opgjort for de fem klynger i slutningen af dette notat, som i 2040 vurderes at udgøre op mod 7 mio. ton CO_2 per år. Omkring 75 pct. af det i denne analyse opgjorte potentiale vurderes altså at have relativt korte transportafstande i områder med andre store udledere, hvilket vurderes at kunne fremme økonomien i nedstrøms dele af værdikæden.
- Fremtiden for anvendelse af biomasse til energiformål, herunder særligt kraftvarme- og varmeproduktion, har afgørende indflydelse på størrelsen af fangstpotentialet. I denne opgørelse medtages anlæg med flere end 2.500 fuldlasttimer i det øvre skøn, hvilket giver et potentiale fra sektoren på knap 2 mio. ton. Hæves grænsen derimod til 3.500 fuldlasttimer, falder potentialet til ca. 0,5 mio. ton, bl.a. i kraft af, at de ca. 1 mio. ton fra Amagerværkets Blok 4 så ikke medregnes. Det øvre spænd for punktkilde-opgørelsen er således særligt sårbar for udviklingen i el- og varmesektoren i perioden 2030-2040, som ikke indgår i KF21.

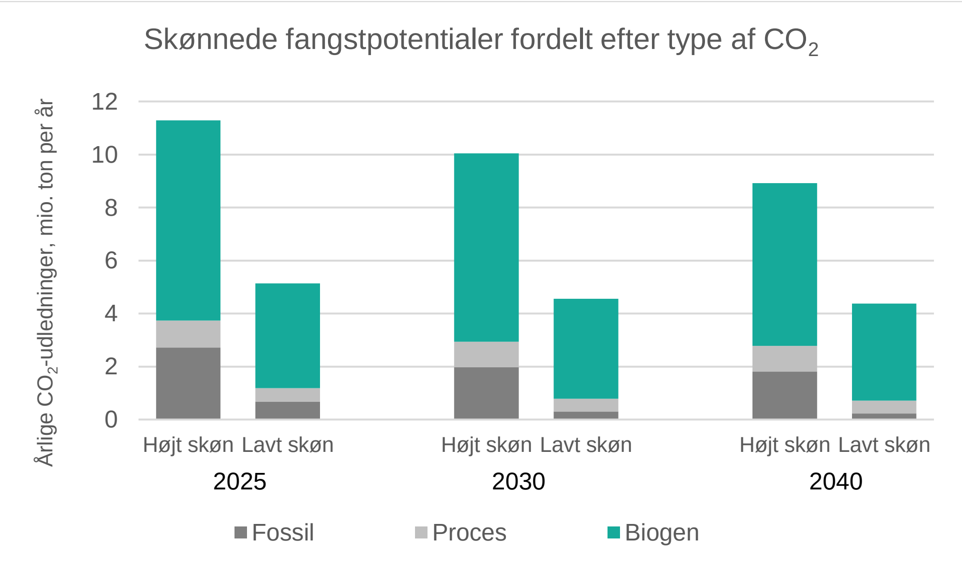
Ovenstående taler dels for, at de nedre skøn for særligt el- og fjernvarmesektoren og i nogen grad affaldssektoren tillægges størst vægt. Anvendelse af potentialer over det nedre skøn kan således medføre risici for, at der bevares CO_2-udledninger fra punktkilder, med afsætning til CCUS, som alternativt ville være lukket eller reduceret af sig selv.

Hertil peger overvejelserne på, at der er behov for en yderligere kvalificering af omkostningerne ved opsamling af CO_2 fra de forskellige punktudledere, og særligt på et behov for øget viden om opsamling af CO_2 fra mindre anlæg med anvendelse af standardkomponenter kendt fra biogasopgradering.

Fossil eller biogen CO_2

Som det fremgår af indledningen, indtager biogen CO_2 en særlig rolle, idet disse kilder kan anvendes til produktion af CO_2-neutrale brændstoffer (CCU) eller negative emissioner til kompensation for udledninger i andre sektorer (BECCS).

Figur 5 viser fangstpotentialet i denne opgørelse fordelt på fossile, biogene og procesudledninger, hvoraf de biogene vurderes at udgøre ca. 3,5-6 mio. ton i 2040. Som nævnt i indledningen bør procesudledninger fra fx cementindustri og raffinaderier medregnes som fossile udledninger. Til sammenligning vurderer Dansk Energi, at potentialet for opsamling af biogen CO_2 i 2040 beløber sig til ca. 4,5 mio. ton. Forskellen mellem DE's opgørelse og det høje skøn i nærværende analyse stammer hovedsageligt fra affaldssektoren og fra industrien. Fsva. affaldssektoren vurderes forskellen at stamme fra overvejelserne om størrelser af punktkilderne, som beskrevet ovenfor, mens forskellen i industrien vurderes at afvige pga. forskellige forudsætninger vedrørende omstilling til VE-gas (biogas og andre grønne gasser som brint) i industrien.



Figur 5 Øvre skøn over opsamlingspotentialer fordelt på biogene, fossile og procesudledninger frem mod 2040. Kilde: Energistyrelsen.

Der må forventes en betydelig efterspørgsel efter biogen CO_2 i fremtiden. Med en simpel omregning af PtX-potentialet i Klimaprogram 2020, anslås et CO_2-behov på op mod ca. 1,5 mio. ton om året i 2030, mens Dansk Energi har opgjort efterspørgslen alene til produktion af PtX-brændstoffer i transportsektoren til 1,8 mio. ton i 2030 og 4,4 mio. ton i 2040. Hertil kommer potentielle behov for grøn CO_2 til negative emissioner.

Det falder uden for formålet med dette notat at opgøre det samlede behov for grøn CO_2 til negative emissioner og PtX-brændstoffer – særligt frem mod klimaneutralitet i 2050. Dansk Energi peger dog på, at der allerede i 2040 vil opstå mangel på grøn CO_2 til dækning af disse behov, hvilket ikke umiddelbart afkræftes af nærværende potentialeopgørelse. En mulig tilgang til denne ubalance kan være øget import af biomasse. En anden kan være udvikling af teknologier til direkte opsamling af CO_2 fra atmosfæren, kaldet DAC (direct air capture), hvilket Klimarådet også peger på[8].

Sektorspecifikke overvejelser

Forskellige karakteristika præger de fire sektorer mht. både CO_2-koncentration i røggassen, antallet af årlige driftstimer, økonomiske forhold og regulering omkring de pågældende aktører, placering og i forhold til usikkerheden om, hvorvidt kilderne er tilgængelige og velegnede til indfangning af CO_2 i 2040.

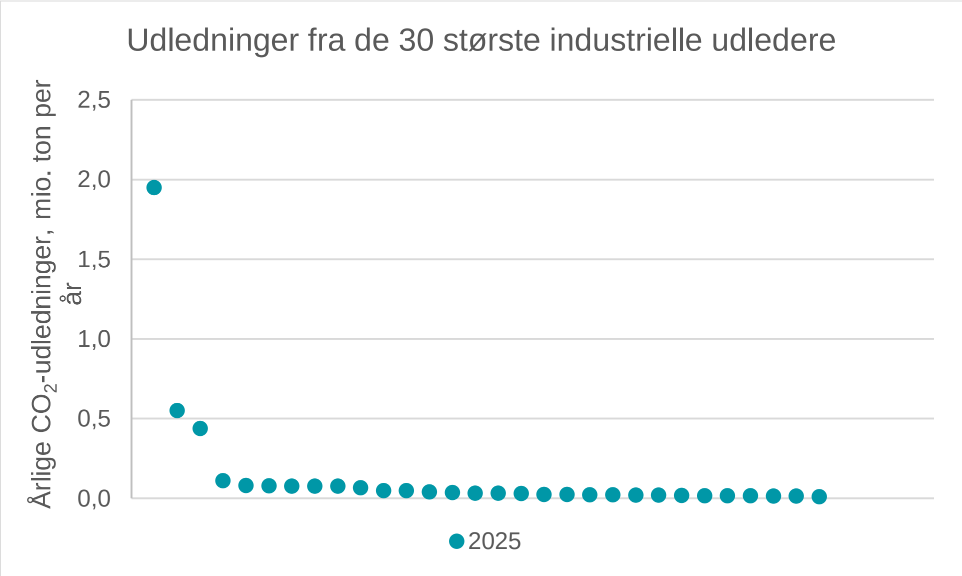
De forskellige sektorer og deres særlige karakteristika ift. CO_2-fangst gennemgås nedenfor, hvoraf det fremgår hvilken tilgang, der er valgt til afskæring ifht. størrelse og vurdering af egnethed til CO_2-opsamling.

Industri

Opgørelsen er baseret på de 30 største industrielle CO_2-udledere i Danmark, som forventes at have samlede udledninger på knap 4,5 mio. tons i 2025, heraf godt 3,5 mio. tons fra fossile udledninger og procesudledninger. Dette skønnes herefter at være stort set uændret frem mod 2040.

Den danske industrisektor er præget af tre meget store udledere, og en lang række mindre og meget små udledere, særligt inden for tegl, fødevarebranchen mv. Dette illustreres i Figur 6, der viser de 30 største industrielle udledere. Efter de tre største udledere, er der kun syv udledere med mere end 50.000 ton CO_2 om året og herefter yderligere syv udledere med mere end 25.000 ton om året.

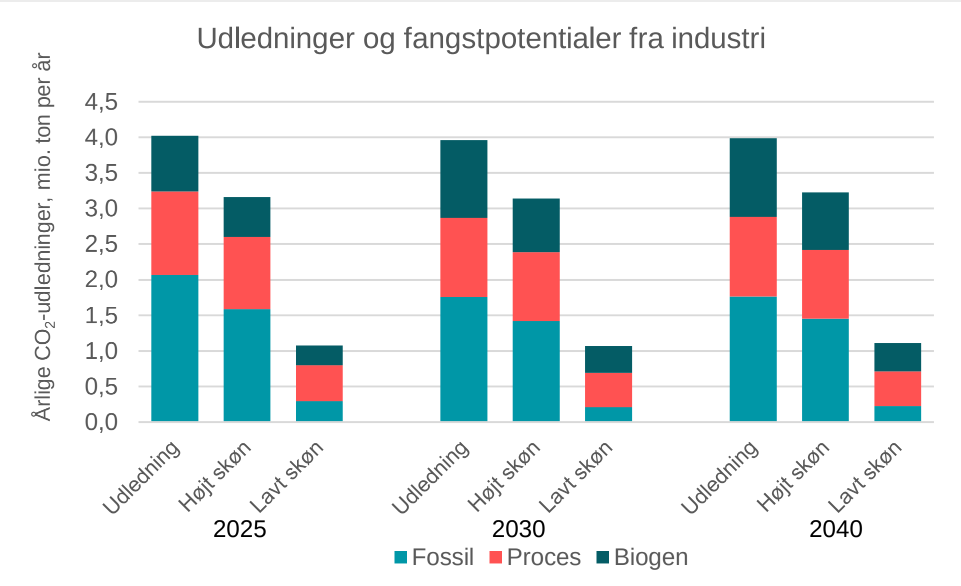
[8] Kendte veje og nye spor til 70 procents reduktion, Klimarådet, 2020, https://klimaraadet.dk/da/rapporter/kendte-veje-og-nye-spor-til-70-procents-reduktion



Figur 6 Størrelser for de 30 største industrielle CO_2-udledere baseret på kvoteregisteret og fremskrevet på baggrund af KF21.

For nogle af de industrielle punktudledere er elektrificering ikke muligt, da de industrielle processer foregår ved høje temperaturer og anvendelse af brændsel direkte i produktionsprocessen, eksempelvis i forbindelse med produktion af cement, kalk, glasuld osv. Disse udledere må forventes fortsat at have et brændselsforbrug – og dermed CO_2-udledninger – fremover. Dog ikke nødvendigvis fossile. Punktudledere med et lavere temperaturbehov, og som pt. anvender gas- eller oliekedler, vil på sigt have et potentiale for at omstille til procesvarmepumper eller andre vedvarende energikilder. Generelt vurderes der at eksistere et betydeligt potentiale for omstilling til VE, elektrificering og energieffektiviseringer i industrien, som i KF21 ikke forventes realiseret uden yderligere tiltag. Det vurderes, at realisering af væsentlige dele af dette potentiale vil være billigere end CCS, og vil kunne forekomme gennem eksempelvis stigninger i ETS kvoteprisen eller nye nationale virkemidler. Dette taler for, at det langsigtede potentiale for CO_2-fangst i industrien er lavere end de fremskrevne udledninger i KF21. Hertil kommer, at der må forventes en vis omlægning fra fossile til biogene udledninger, særligt fra skift fra naturgas til biogas som følge af den stigende VE-andel i gasnettet. Dette afspejles i et sænket ”lavt skøn” for industrisektoren.

Der antages en minimumsstørrelse på 50.000 ton CO_2 per år for industrielle punktudledere i opgørelsen af det fangstpotentialet. Det samlede fangstpotentiale i industrien bliver dermed omkring 1-3 mio. ton CO_2 per år, jf. Figur 7.



Figur 7 Samlede udledninger og fangstpotentialer for CO_2-opsamling i industrien. De samlede udledninger er baseret på oplysninger fra kvoteregisteret, som er fremskrevet på baggrund af KF21 og herefter forlænget frem til 2040. Forlængelsen frem mod 2040 er ikke en del af den konsoliderede fremskrivning, og er derfor forbundet med væsentlig usikkerhed Fangstpotentialer er begrænset til udledere over 50.000 ton per år, og heri indgår endvidere nedenstående eksempelberegning for Aalborg Portlands annoncerede omstilling til ledningsgas.

Aalborg Portland

Cementfabrikken Aalborg Portland er landets største industrielle udleder af CO_2, og forventes i KF21 at udlede godt 2,2 mio. ton CO_2 i 2030. Produktionen og dermed udledningen af CO_2 vurderes at være relativt konstant året rundt. CO_2-koncentrationen i røggassen anslås til ca. 16 pct. for cementfabrikker generelt.[9]

Aalborg Portland indgik i september 2020 en aftale med regeringen om at sikre CO_2-reduktioner på samlet set 660.000 tons per år og til at samarbejde om yderligere reduktioner[10]. Dele af denne aftale indgår i vurderingen af udledningerne fra Aalborg Portland i KF21's grundforløb[11].

I foråret 2021 indgik virksomheden endvidere en aftale med Evida[12] om forsyning med ledningsgas fra 2022. Det danske gasnet indeholder omkring 20 pct. opgraderet biogas iblandet den fossile naturgas og forventes i Energistyrelsens

[9] https://www.spglobal.com/platts/en/market-insights/latest-news/coal/010820-us-45q-tax-credit-key-to-developing-carbon-capture-facility-in-colorado

[10] Klima-, energi og forsyningsministeriet, 2020, https://kefm.dk/aktuelt/nyheder/2020/sep/aalborg-portland

[11] KF21 forudsætningsnotat om cementproduktion, Energistyrelsen, 2021, https://ens.dk/sites/ens.dk/files/Basisfremskrivning/7d_kf21_forudsaetningsnotat_-_cementproduktion.pdf

[12] Evida, 2021, https://evida.dk/nyheder/evida-kobler-aalborg-portland-pa-gasnettet/

Analyseforudsætninger til Energinet 2020 (AF20) at stige til op mod 100 pct. i 2040. Dette kan bidrage til at sænke udledningerne fra Aalborg Portland, da naturgas udleder mindre CO_2 per GJ energiindhold end den petrokoks, som Aalborg Portland bl.a. anvender i dag. Gasnettets stigende andel af biogas vil desuden give anledning til et delvist skift fra fossile til biogene CO_2-udledninger. Den præcise udformning af de tekniske løsninger og de resulterende udledninger fra Aalborg Portland i fremtiden er ikke kendt. I denne opgørelse er det derfor antaget, at det i KF21 forventede energiforbrug af kul og petrokoks erstattes 1:1 med ledningsgas, hvor der er forsøgt at tage højde for den lavere energitæthed i gas ift. kul og petrokoks, hvilket giver anledning til lavere samlede udledninger og let stigende biogene udledninger.

En omlægning af Aalborg Portlands produktion til gas skaber en væsentligt øget efterspørgsel efter ledningsgas, uden der nødvendigvis skabes et større udbud af opgraderet biogas. Denne effekt vurderes – alt andet lige – at ville sænke andelen af opgraderet biogas i nettet for øvrige aftagere af ledningsgas i opgørelsen.

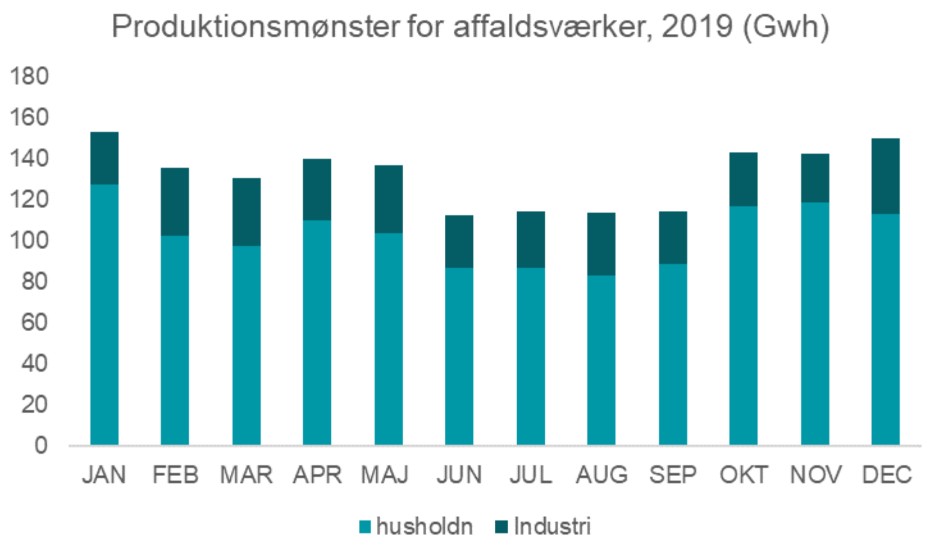
Raffinaderierne

Equinor og Shell raffinaderierne i hhv. Kalundborg og Fredericia forventes i KF21 at udlede knap 1 mio. ton CO_2 tilsammen i 2030 og er dermed de næststørste udledere af CO_2 i den industrielle sektor. Raffinaderiernes rolle i det fremtidige energisystem er uvis, og de fremtidige udledninger herfra er derfor behæftet med betydelig usikkerhed. Frem mod 2040 forventes der dog stadig at være et forbrug af olieprodukter. På linje med øvrige industrivirksomheder vurderes fangstpotentialet fra raffinaderierne at ligge lavere end de samlede udledninger opgjort i KF21.

Affaldsforbrænding

Udledningerne fra affaldsforbrænding forventes at være knap 4 mio. tons i 2025, og forventes i KF21 at falde til ca. 3 mio. tons i 2030, bl.a. som følge af aftalen om *Klimaplan for en grøn affaldssektor og cirkulær økonomi* fra juni 2020. Herefter vurderes kun et mindre fald frem mod 2040. Heraf forventes fossile udledninger at udgøre ca. 0,5 mio. ton i 2040. De tre største punktkilder forventes under betydelig usikkerhed at udgøre knap 1,5 mio. tons i 2040. Den største udleder af CO_2 blandt affaldsværkerne er Amager Ressourcecenter (ARC).

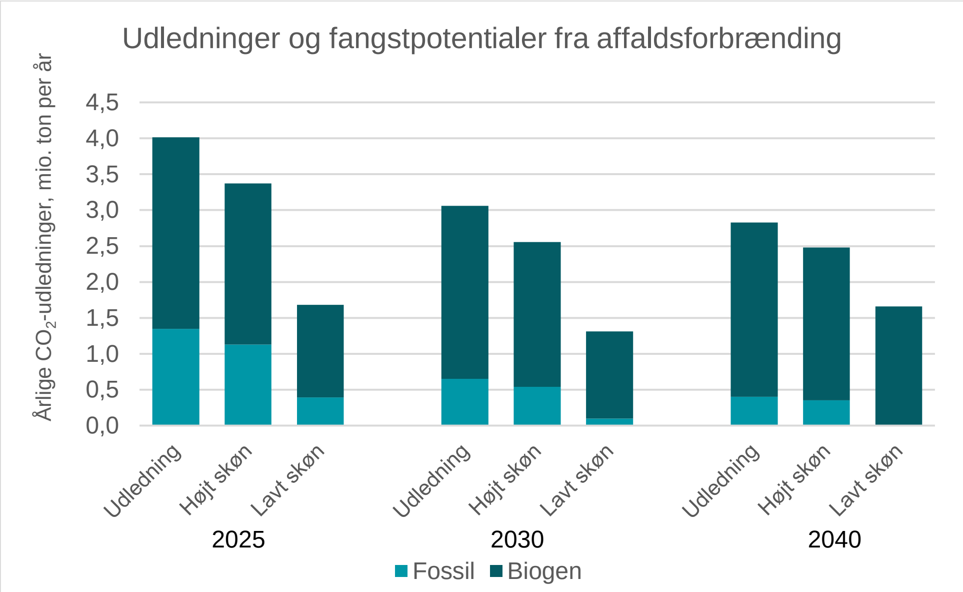
Affaldsforbrændingsanlæg er generelt kendetegnet ved at køre i fuld drift det meste af året, da driften defineres af behovet for behandling af affald og ikke af et svingende forbrug af el og fjernvarme. Dette er illustreret i Figur 8 nedenfor, hvor brændselsforbruget til afbrænding af affald er vist for 2019. Her fremgår det, at variationen over året er begrænset. Det betyder, at udledningen af CO_2 hen over året ligeledes forventes at være stabil. I fremskrivningen, der ligger til grund for denne opgørelse, vurderes alle affaldsforbrændinger at have høje antal fuldlasttimer – typisk mellem 6.000 og 8.000 fuldlasttimer.



Figur 8 Brændselsforbrug på affaldsforbrændingsanlæg hen over året i 2019.
Kilde: Hovedbrændselsopgørelsen.

Den stabile drift medvirker til at sænke omkostningerne til afskrivning af fangstanlægget. I tillæg hertil kommer, at affaldsforbrænding frem mod 2040 vurderes fortsat at indeholde en fossil fraktion, som de fortrinsvist kommunalt ejede affaldsforbrændingsanlæg må forventes at have ønsker om at håndtere som end el af lokale målsætninger. Affaldsforbrændingsanlæg må derfor forventes at have relativt lave interne forrentningskrav.

Baseret på ovenstående medtages CO_2-udledninger fra affaldsforbrændingsanlæg med flere end 50.000 ton CO_2 om året i opgørelsen af fangstpotentialet, som vurderes at være knap 1,5-2,5 mio. ton per år i 2040, jf. Figur 9. Det lave skøn repræsenterer en situation, hvor kun de største anlæg i de største byer etablerer CO_2-fangst.



Figur 9 Samlede udledninger og fangstpotentiale for affaldsforbrænding. Fangstpotentialet er begrænset til udledere over 25.000 ton per år for det høje skøn og til udledere over 100.000 ton per år i de største byer for det lave skøn. Kilde: Energistyrelsen.

El- og fjernvarmeproduktion

CO_2-udledningerne fra el- og fjernvarmeproduktion kommer i dag primært fra de store centrale kul-, og biomassefyrede kraftvarmeværker. Kraftvarmeværkerne og en lang række rene varmeværker forventes samlet set at stå for en udledning på ca. 7,5 mio. ton CO_2 i 2030, som primært kommer fra de centrale, biomassefyrede værker. Ca. 3,5 mio. tons kommer fra de ti største centrale værker og omkring 2,0 mio. ton fra sektorens tre største udledere. I perioden efter 2030 forventes flere store kraftværksblokke at lukke, jf. bl.a. Energistyrelsens *Analyseforudsætninger til Energinet 2020* (AF20)[13]. Herefter vurderes omkring halvdelen af sektorens resterende punktkildeudledninger på i alt ca. 6,5 mio. ton at stamme fra de 8 største punktkilder. Såfremt der indføres initiativer til reduktion af biomasseforbruget i Danmark, jf. nedenfor, må CO_2-udledningerne herfra forventes reduceret tilsvarende.

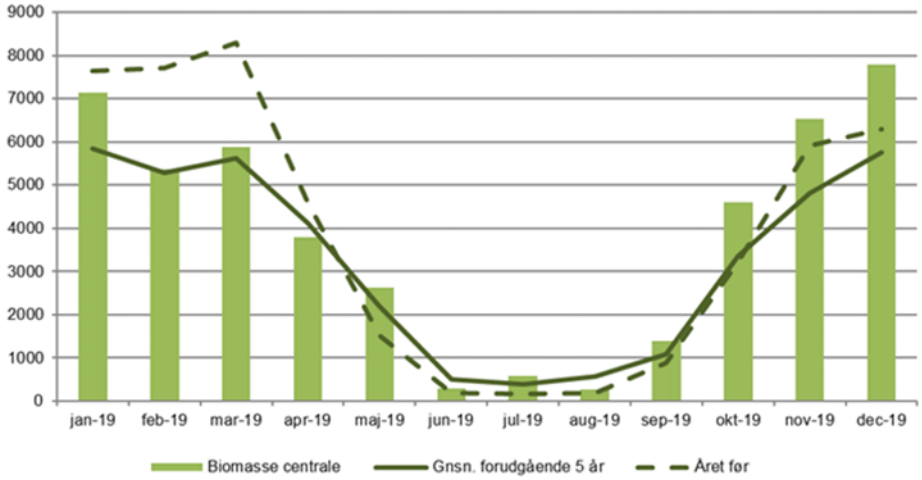
Den største udleder for denne sektor forventes at være Amagerværkets Blok 4. Det sidste kulfyrede værk forventes at blive udfaset i 2028, og det vil således kun være udledninger fra biomasseværker, som potentielt kan indfanges. CO_2-koncentrationen i røggassen på biomasseværkerne anslås at være ca. 10-13 pct.

Opsamling af CO_2 fra biomassekraftvarmeværker

Produktionen på biomassekraftvarmeværkerne følger i høj grad varmeefterspørgslen, og udledningen herfra er derfor begrænset i sommerhalvåret, jf. Figur 10. Dette medfører, at fangstanlæg samt nedstrømsanlæg som CO_2-

[13] Energistyrelsens analyseforudsætninger til Energinet, 2020, https://ens.dk/service/fremskrivninger-analyser-modeller/analyseforudsaetninger-til-energinet

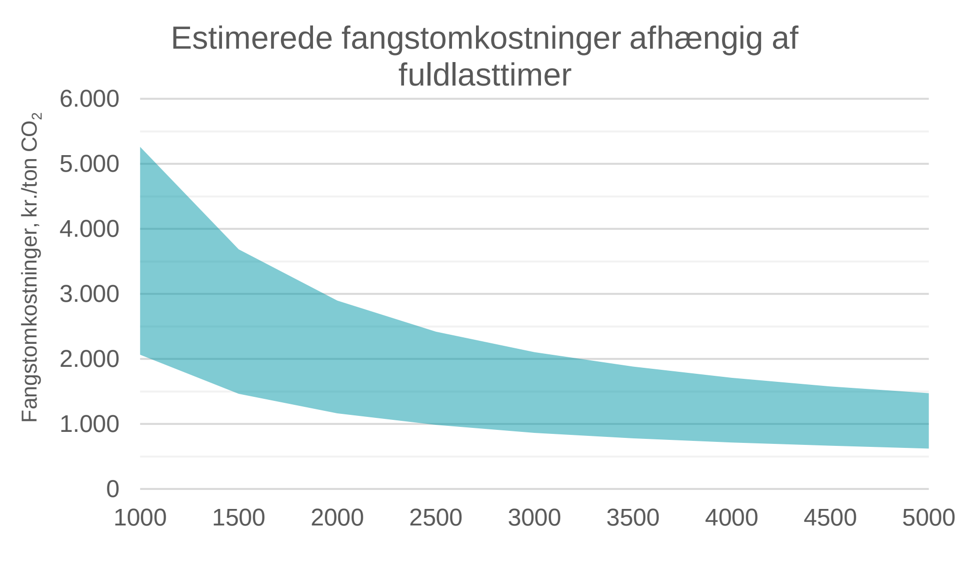
rensning, komprimering, transport og mellemlagring har behov for stor kapacitet til at dække det høje forbrug i vintermånederne, mens der vil være stor ledig kapacitet i sommermånederne.



Figur 10 Biomasseforbrug på centrale kraftvarmeværker fordelt hen over året i 2019 og foregående år. Enhed i TJ. Kilde: Energistyrelsens Energistatistik

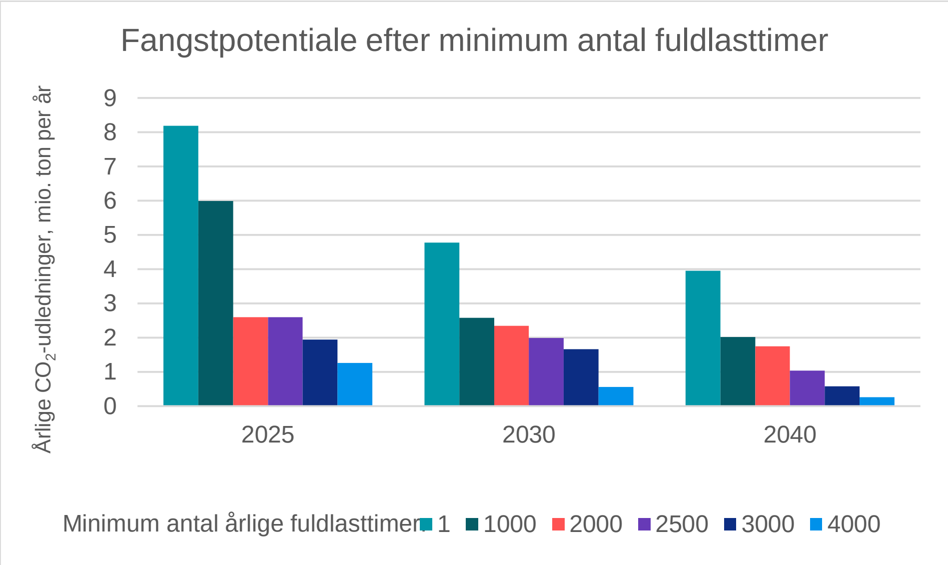
Et mål for, i hvor høj grad kapaciteten i et anlæg udnyttes, er anlæggets antal af såkaldte fuldlasttimer på et år. Hvis et anlæg har 8760 fuldlasttimer, er 100 pct. af kapaciteten udnyttet i alle årets 8760 timer. Har et anlæg derimod 4380 fuldlasttimer (halvdelen af 8760), svarer det til, at anlægget kører med halv kapacitetsudnyttelse i alle årets timer eller fuld kapacitetsudnyttelse i halvdelen af årets timer. Eller en kombination af disse. Typiske grundlastanlæg som flisfyrede kraftvarmeværker har i dag typisk mellem 4.500 og 5.000 fuldlasttimer om året.

De store udsving i produktionen betyder, at kapaciteten på både varmeproduktionsanlægget og fangstanlægget udnyttes dårligere, da der i mange timer vil være uudnyttet kapacitet. Dermed må afskrivningerne på investeringen i et fangstanlæg fordeles på færre ton opsamlet CO_2. Dette øger omkostningerne per ton CO_2 til afskrivning af anlægget markant, som eksempelberegningerne i Figur 11 viser. Dette vurderes at gælde for alle kraftvarme- og fjernvarmeanlæg, selvom udsvingene vurderes at være mere udtalte for de store anlæg i de store fjernvarmeområder, hvor affaldsforbrænding og overskudsvarme typisk dækker det meste af varmebehovet om sommeren.



Figur 11 Regneeksempel for fangstomkostninger ved et "post-combustion" anlæg til CO2-fangst afhængig af antallet af årlige fuldlasttimer på anlægget. Kilde: Energistyrelsens teknologikatalog for "Post combustion – large biomass".

Ovenstående har også en markant indflydelse på det økonomiske potentiale for opsamling af CO_2 fra el- og fjernvarmeproducerende anlæg. Dette illustreres i Figur 12, der viser det samlede potentialet for CO_2-fangst fra alle anlæg over 50.000 ton CO_2 per år, afhængig af hvor mange fuldlasttimer der kræves for, at anlægget tælles med. Den grønne kolonne til venstre for hvert år viser alle anlæg med mindst 1 fuldlasttime om året (alle anlæg i drift), mens fx den røde kolonne viser potentialet fra alle anlæg med mindst 2.000 fuldlasttimer om året osv.



Figur 12 Fangstpotentialer i 2025, 2030 og 2040 opgjort for anlæg over 50.000 ton CO_2 per år med forskellige minimum antal af årlige fuldlasttimer. Enkelte fossile kraftvarmeværker indgår i figuren, uden at det flytter på konklusionen. Kilde: Energistyrelsen.

CO_2-fangst fra el- og fjernvarmeanlæg er altså økonomisk udfordret pga. relativt lave antal driftstimer. Dermed bliver kravene til placering af biomassefyrede anlæg større, fordi der kræves kortere transportafstande og storskalafordele i forbindelse med fx klynger af andre udledere, hvor transportinfrastruktur mv. kan deles med andre anlæg.

Biomasseforbruget i fremtiden

Biomasseværkernes driftsmønster og fremtid særligt i et længere perspektiv er usikkert pga. øget konkurrence fra andre kilder mv. På baggrund af *Klimaaftalen for Energi og Industri 2020* er en analyse under udarbejdelse, der skal vurdere konsekvenserne for biomasseforbruget, elforsyningssikkerhed, fjernvarmepriser mv. forbundet med forskellige tilgange til at begrænse anvendelsen af biomasse til energiformål. Analysen er ikke færdig. Men det vurderes indledningsvis, at en begrænsning af biomasseforbruget kan medføre tre overordnede tendenser:

1. Begrænsning af forbrug medfører færre, mindre biomassebaserede punktkilder og dermed færre CO_2-udledninger.
2. Af hensyn til forsyningssikkerhed vedr. både el- og varmeforsyning, kan en række biomassefyrede anlæg forventes fastholdt – dog evt. i ændrede roller, hvor de i højere grad anvendes som spidslastanlæg for fjernvarmenettet og spids- og reservelastanlæg i elsystemet. Der vurderes dog også at være en vis sandsynlighed for at disse ydelser i stigende omfanget bliver leveret af gasturbiner og gasmotorer baseret på biogas. Dette vurderes at kunne medføre et sænket antal fuldlasttimer for de pågældende anlæg.

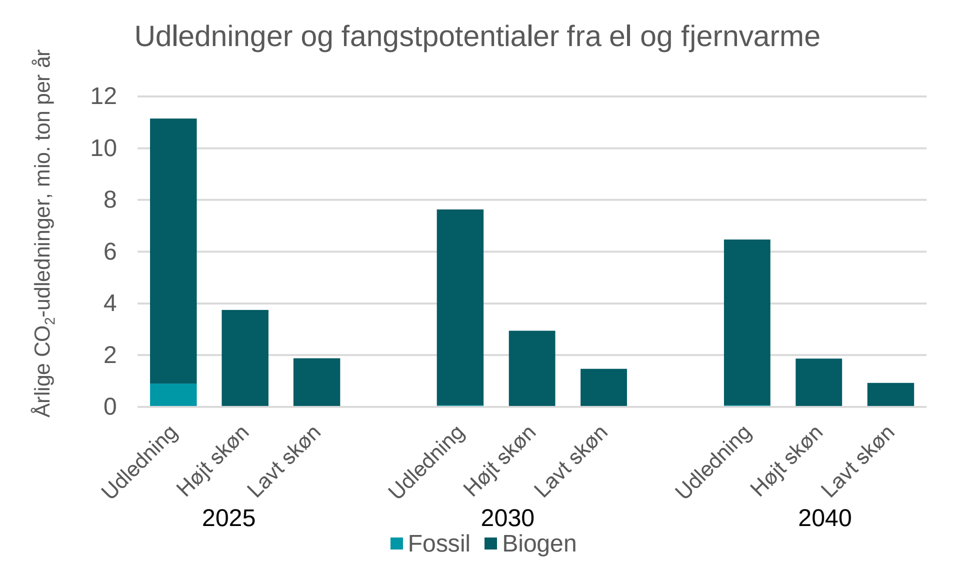
3. Der kan muligvis også forventes et lagsigtet skift væk fra biomassefyrede kraftvarmeværker over mod biomassekedler til ren varmeproduktion i vinterhalvåret som supplement til varmepumper og overskudsvarme.

Alle tre effekter må forventes at medføre forringede økonomiske vilkår for angst, lagring og anvendelse af CO_2 fra de større punktkilder, mens mindre punktkilder, under betydelig usikkerhed vurderes at levere hovedparten af udledningerne.

En mulig modsatrettet effekt kan opstå, såfremt der etableres et marked for opsamlet CO_2 eller på anden måde gives økonomiske incitamenter til CO_2-fangst. Det kan ikke udelukkes, at sådanne økonomiske incitamenter kan forbedre driftsøkonomien i biomassekraftvarmeværker og biomasse-varmeværker. Dette kan give eksisterende anlæg flere driftstimer, eller give incitamenter til fastholdelse, levetidsforlængelse eller etablering af nye biomasseforbrugende anlæg. Dette er ikke nærmere analyseret i nærværende analyse.

De store biomassefyrede værker, som er etableret/konverteret for nyligt, må dog forventes at producere en vis periode fremover, uanset hvilken tilgang, der vælges.

Baseret på ovenstående vurderes el- og fjernvarmeproducerende anlæg at være relevante for CO_2-opsaling i størrelser over 50.000 ton CO_2 per år. Samtidig vurderes anlæg med mindre end 2.500 årlige fuldlasttimer at medføre for høje omkostninger til at det er rentabelt at opsamle CO_2'en, jf. Figur 11. Dermed skønnes fangstpotentialet fra el- og fjernvarmeproduktion omkring 1-2 mio. ton per år i 2040, jf. Figur 13. Det vurderes, at det mest sandsynlige udfald ligger i den nedre del af spændet.

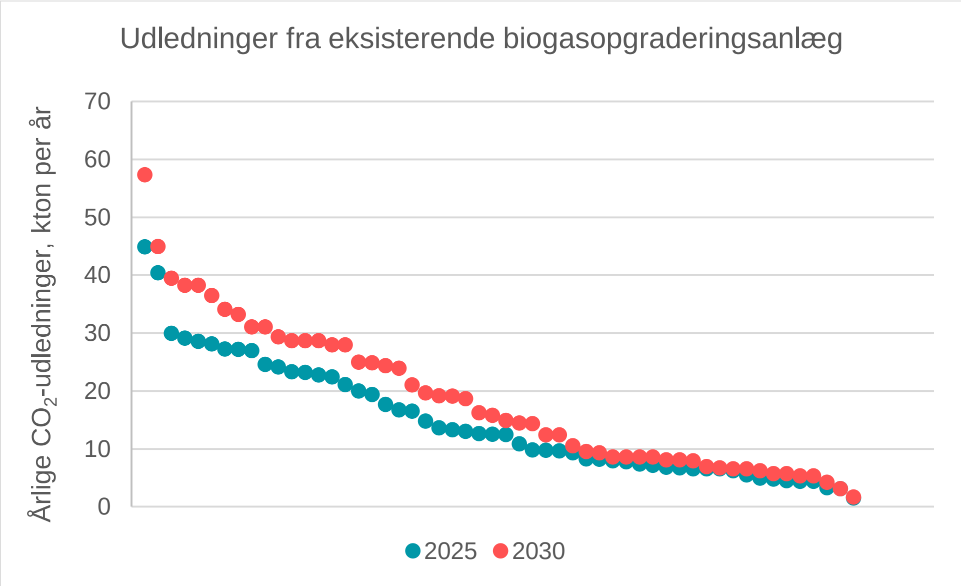


Figur 13 Samlede udledninger og fangstpotentiale for CO_2-opsamling fra el- og fjernvarmeproducerende anlæg. Det høje skøn er begrænset til udledere over 50.000 ton per år. Kilde: Energistyrelsen.

Anlæg til opgradering af biogas

Biogas fra biogasanlæg indeholder generelt omkring 60-70 pct. metan og omkring 30-40 pct. CO_2. Som et led i opgraderingen af biogassen forud for indfødning i gasnettet, separeres og udledes CO_2-fraktionen ved hjælp af aminbaseret CO_2-fangst på samme måde som røggas kan renses på kraftværker eller lign. Den udledte CO_2 stammer fra biomasseinputtet i anlægget, og opfattes som klimaneutral.

Der er i dag ca. 50 opgraderende biogasanlæg i Danmark. Der er store forskelle på produktionen på de enkelte anlæg og dermed også på CO_2-udledningerne, som vurderes at ligge mellem ca. 1.000 og ca. 50.000 ton per år. Figuren viser den årlige CO_2-udledning fra de 54 eksisterende biogasopgraderingsanlæg i Danmark.



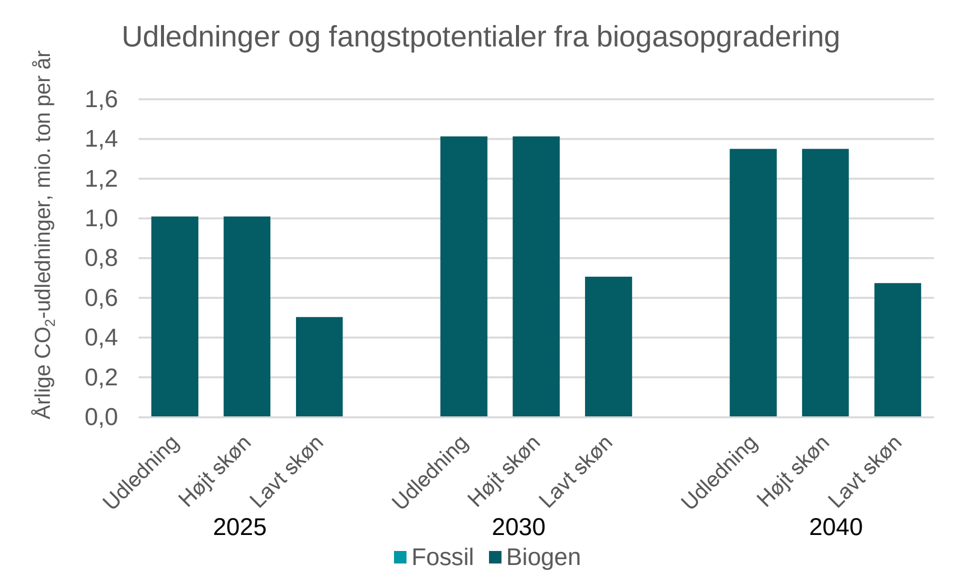
Figur 14 Årlige udledninger fra kendte biogasopgraderingsanlæg i Danmark baseret på KF21 for 2025 og 2030.
Kilde: Energistyrelsen.

Biogasprognosen og KF21 indeholder en fremskrivning af produktionen for de eksisterende anlæg til 2030 samt en vurdering af den yderligere produktion, der vil komme som følge af de seneste biogasudbud samt de udbud til biogas og andre grønne gasser, der forventes iværksat fra 2022 eller 2023. De langsigtede udledninger er fastholdt fra 2030 til 2040, dog med en mindre justering som følge af ophør af støtteordninger i starten af 2030'erne.

Det forventes, at nye, kommende biogasanlæg vil være i samme størrelsesorden som de større anlæg bygget i 2019 og 2020. Derfor medregnes de kommende anlæg alle med størrelser over 50.000 ton per år.

Som beskrevet separeres CO_2 allerede i dag fra biogassen som led i opgraderingsprocessen. CO_2-udledningerne fra biogasanlæg er derfor i princippet klar til anvendelse. Dermed får punktkildens størrelsen mindre betydning for økonomien i opsamling. Der vurderes dog at være behov for yderligere rensning og komprimering samt evt. et mellemlager, såfremt CO_2-en skal klargøres til transport eller anvendes, hvilket dog vil være forbundet med markant lavere omkostninger end CO_2-fangst fra røggas på større anlæg. Hertil kommer, at der kan være en øget betalingsvillighed for CO_2 fra biogasanlæg, da den anvendte biomasse i mindre grad er udfordret mht. bæredygtighed og klimaneutralitet end fx importeret træbiomasse i centrale kraftværker. Derfor inkluderes alle biogasopgraderingsanlæg i opgørelsen.

Det samlede CO_2-fangstpotentiale for biogasopgradering skønnes dermed at være omkring 0,5-1 mio. ton CO_2 i 2025 og forventes at stige til 0,7-1,3 mio. ton i 2040.



Figur 15 Samlede udledninger og fangstpotentiale for CO_2-opsamling fra biogasopgraderingsanlæg. Det samlede potentiale er baseret på KF21 frem til 2030, hvorefter produktion og dermed udledninger er fastholdt med en mindre justering frem til 2040. Alle kendte og forventede biogasanlæg er medtaget i det økonomiske potentiale.

Opgørelse af potentialet efter omkostninger

Som beskrevet ovenfor, er der store forskelle på omkostningerne forbundet med CO_2-fangst fra forskellige typer af anlæg baseret på størrelse, driftsmønster, anlægstype mv. I det følgende anskueliggøres dette gennem en opdeling af det vurderede fangstpotentiale efter omkostningerne til fangst af CO_2'en.

Fangstomkostningerne er beregnet for hvert enkelt anlæg, der indgår i analysen på baggrund af de fremskrevne udledninger samt fremskrevne eller antagne antal af årlige fuldlasttimer. Der medregnes ikke omkostninger til transport eller mellemlagring af CO_2. Fordelingen afspejler derfor ikke variation i omkostninger ift. anlæggenes placering. Metoden for beregningerne er beskrevet i *Bilag 1 – Metode*.

Tabel 2 viser fordelingen af potentialet afhængig af, hvilken øvre grænse, der lægges for fangstomkostningerne. Der tages udgangspunkt i det øvre potentialeskøn jf. ovenfor.

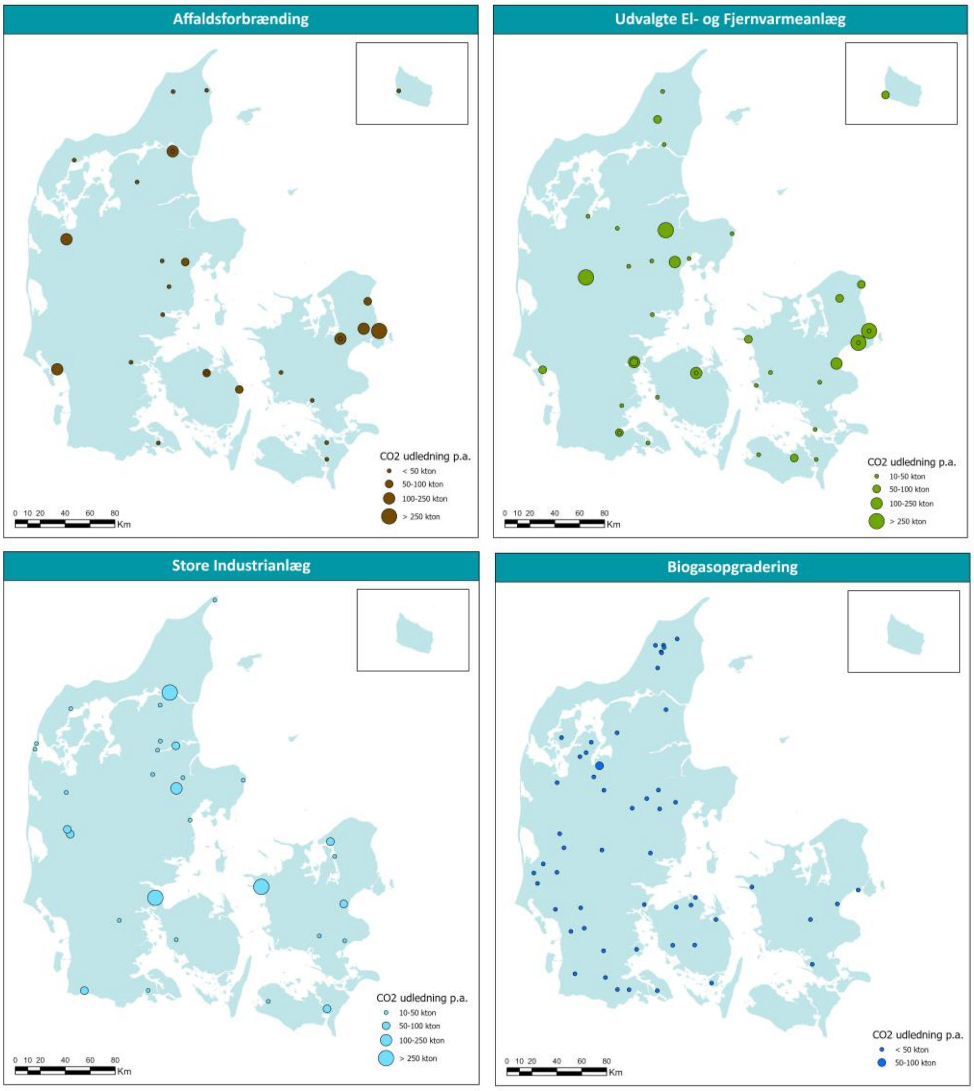
Tabel 2 Fordeling af fangstpotentialet efter omkostninger til fangst

Enhed: mio. ton CO_2/år	2040-udledninger		< 600 kr./ton		< 800 kr./ton		< 1.000 kr./ton		< 1.200 kr./ton	
	Fossil	**Biogen**	**Fossil**	**Biogen**	**Fossil**	**Biogen**	**Fossil**	**Biogen**	**Fossil**	**Biogen**
Affaldsforbrænding	0,4	2,4	0,2	1,4	0,3	2,1	0,4	2,1	0,4	2,1
Fjernvarme	0,1	6,4	0,0	0,1	0,0	0,3	0,0	1,9	0,0	1,9
Industri	3,4	0,8	0,0	0,0	0,1	0,2	2,4	0,8	2,4	0,8
Biogasopgradering	0,0	1,3	0,0	1,3	0,0	1,3	0,0	1,3	0,0	1,3
Sum	**3,9**	**11,0**	**0,2**	**2,8**	**0,4**	**3,9**	**2,8**	**6,1**	**2,8**	**6,1**
Total	**14,9**		**3,0**		**4,3**		**8,9**		**8,9**	

Fordelingen af fangstpotentialet i Tabel 2 opgøres efter en øvre grænse for fangstomkostningerne. Til sammenligning vurderes omkostningerne til transport mellemlagring og lagring i undergrunden at udgøre i omegnen af 200-600 kr./ton afhængig af punktkildernes beliggenhed, transportformer, lagerets udnyttelse og en række antagelser. I dette notat er potentialet indledningsvist opgjort for øvre grænser på hhv. 600, 800, 1.000 og 1.200 kr./ton, jf. tabellen.

Geografisk fordeling af punktkilder

De forskellige punktkilder til CO_2 ligger spredt ud over landet efter forskellige trends: Affaldsforbrændinger og fjernvarmeanlæg ligger fx omkring større byer, mens biogasopgraderingsanlæg typisk ligger på landet. Figur 16 viser fordelingen af punktkilder for de fire sektorer behandlet i dette notat.



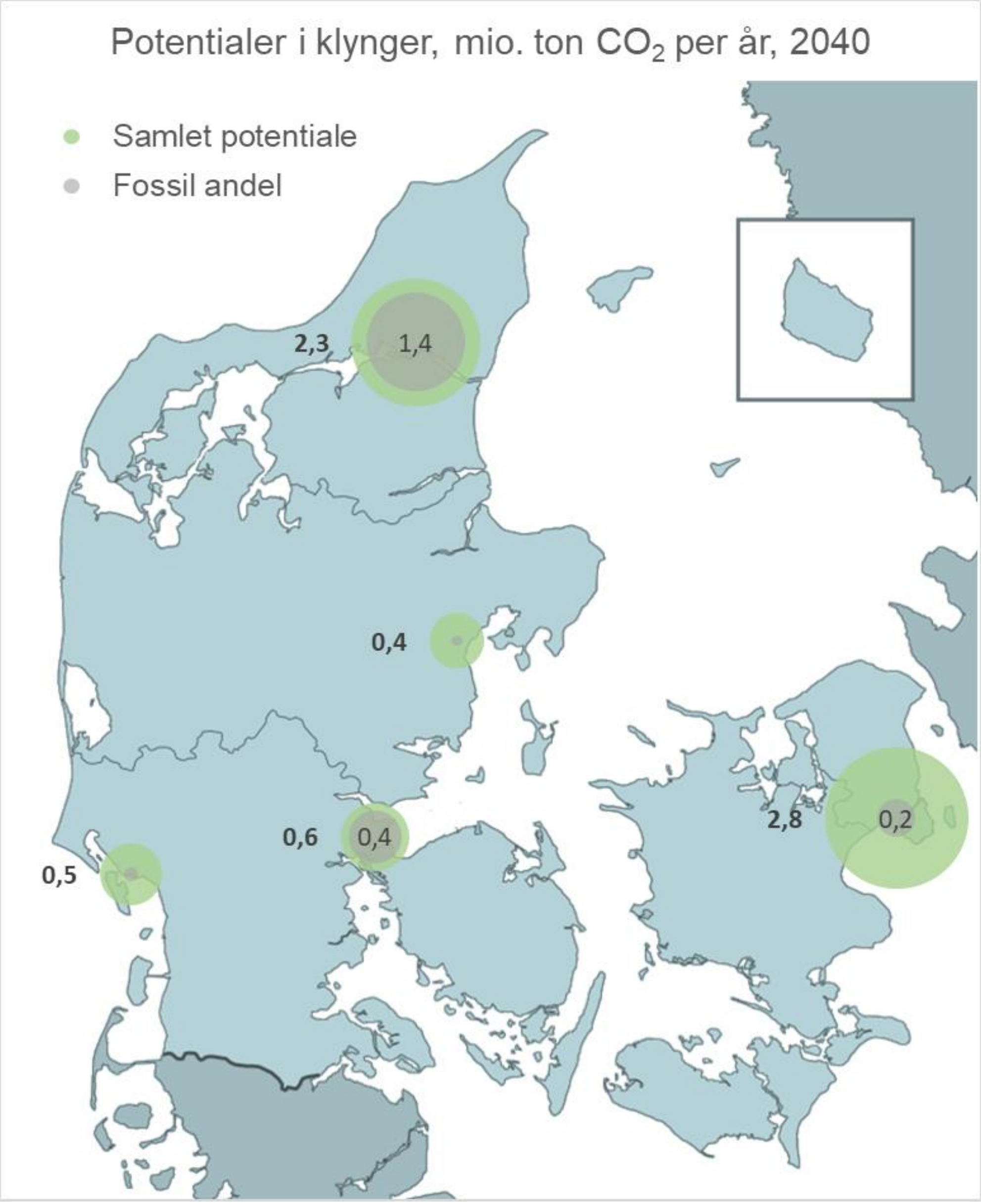
Figur 16 CO_2-punktkilder for de fire opgjorte sektorer i 2040. Kilde: Energistyrelsen

De store punktkilder i fremtiden er koncentreret omkring store og større byer. Dette kommer særligt af, at affaldsforbrænding og de største fjernvarmeproducenter udgør hovedparten af potentialet, og at disse anlæg normalt er placeret i eller i nærheden af de byer, de servicerer.

På denne baggrund, er det høje skøn for fangstpotentialet opgjort for fem forskellige geografiske områder centreret omkring København, Aalborg, Aarhus, Esbjerg og Fredericia. Dette fremgår af Tabel 3 nedenfor. For hvert område er udledningerne fra de største udledere (særligt affaldsforbrænding og store kraftvarmeanlæg) opgjort. Udledningerne fra de enkelte virksomheder aggregeres af hensyn til potentielt kommerciel følsomhed af oplysningerne. Opgørelserne er særligt følsomme over for fremtiden for de biomassefyrede kraftvarmeværker, som forventes delvist udfaset gennem perioden, men som potentielt kan opnå forbedret driftsøkonomi, hvis der gives økonomiske incitamenter til CCS. Herunder vises de øvrige udledninger i potentialeopgørelsen i nærheden af de store punktkilder aggregeret for hver sektor. Disse opgørelser er behæftet med betydelig usikkerhed, og afhænger af de valgte transportafstande for punktkilder i oplandet. Figur 16 viser en geografisk fremstilling af punktkilderne, som er indeholdt i de fem klynger i Tabel 3.

Tabel 3 Fangstpotentialer for punktkilder fordelt i geografiske områder. Skønnene er behæftet med stor usikkerhed, da de afhænger af de valgte transportafstande. Summen er mindre end summen af de enkelte klynger, da der er overlap mellem oplandet til Esbjerg og Fredericia.

	Samlede udledninger, mio. ton CO_2/år			Biogene udledninger, mio. ton CO_2/år			Fossile udledninger, mio. ton CO_2/år		
	2025	**2030**	**2040**	**2025**	**2030**	**2040**	**2025**	**2030**	**2040**
Storkøbenhavn	4,3	3,1	2,8	3,7	2,8	2,6	0,6	0,3	0,2
Nordjylland	2,1	2,2	2,3	0,6	0,8	0,9	1,6	1,3	1,4
Århus	1,6	0,6	0,4	1,5	0,6	0,4	0,0	0,0	0,0
Esbjerg	0,5	0,5	0,5	0,5	0,5	0,5	0,1	0,0	0,0
Fredericia	0,8	0,7	0,6	0,4	0,3	0,2	0,4	0,4	0,4
Sum	**9,3**	**7,0**	**6,7**	**6,6**	**4,9**	**4,7**	**2,7**	**2,1**	**2,0**

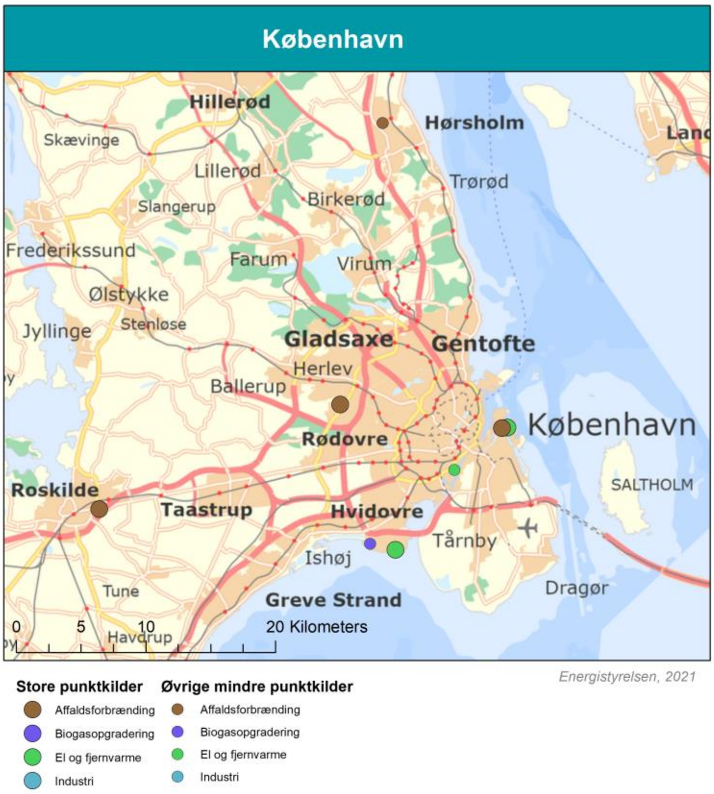


Figur 17 Geografisk fremstilling af de fem identificerede klynger fra Tabel 3. Størrelsen af den grønne cirkel angiver den samlede udledning i klyngen i 2025, mens den grå cirkel viser den andel, der stammer fra fossile brændsler og procesudledninger.

Tallene er udspecificeret for de enkelte geografiske områder i det følgende.

Storkøbenhavn

Samlingen af store CO_2-udledere omkring København vurderes i 2040 at omfatte Amager Ressourcecenter (ARC), Vestforbrænding, Amagerværkets Blok 4, Avedøreværket og ARGO i Roskilde. Ud over disse store punktkilder indeholder klyngen få mindre anlæg, afhængig af hvilken afstand der lægges til grund. Udlederne er illustreret i Figur 17 og potentialet er vist i Tabel 4. Avedøreværket er medtaget, selvom værket i denne opgørelse vurderes at have for få årlige fuldlasttimer i 2040 til, at CO_2-opsamling vil være rentabel og anlægget ikke forventes at være i drift efter 2040, jf. Energistyrelsens analyseforudsætninger til Energinet. Denne vurdering er dog særdeles usikker, og værket er derfor medtaget her. Det er derfor væsentligt at være opmærksom på, at eventuelle CCUS-anlæg knyttet til Avedøreværket kan medføre, at der udledes og fanges CO_2 fra anlægget som alternativt ville have væsentligt færre driftstimer eller være helt lukket. Det samme gør sig principielt gældende for andre anlæg.



Figur 18 Overblik over punktkilder i Storkøbenhavn. Kilde: Energistyrelsen.

Tabel 4 Fangstpotentialer for store og små punktkilder omkring Storkøbenhavn. Der er anvendt samme skæringspunkter vedr. størrelser og antal fuldlasttimer som for sektoropgørelserne i øvrigt. Udledningerne fra de enkelte virksomheder er aggregeret af hensyn til potentielt kommerciel følsomhed af oplysningerne.

	Samlede udledninger, mio. ton CO_2/år			Biogene udledninger, mio. ton CO_2/år			Fossile udledninger, mio. ton CO_2/år		
	2025	**2030**	**2040**	**2025**	**2030**	**2040**	**2025**	**2030**	**2040**
Store udledere	4,3	2,9	2,7	3,7	2,6	2,5	0,6	0,3	0,2
- Amager Ressourcecenter									
- Vestforbrænding									
- Amagerværket, Blok 4									
- Avedøreværket									
- ARGO									
Øvrige mindre udledere									
- Affaldsforbrænding	0,0	0,1	0,2	0,0	0,1	0,1	0,0	0,0	0,0
- El og fjernvarme	0,0	0,1	0,0	0	0,1	0	0,0	0,0	0,0
- Industri	0,0	0,0	0,0	0	0	0	0	0	0
- Biogasopgradering	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
Sum	**4,3**	**3,1**	**2,8**	**3,7**	**2,8**	**2,6**	**0,6**	**0,3**	**0,2**

Noter.:
[1]: Avedøreværket forventes at have for få driftstimer fremover til at være inkluderet i det samlede potentiale for CO_2-fangst i Danmark. Anlægget er medtaget i denne klyngeangivelse, eftersom det også indgår i C4-samarbejdet i Hovedstadsområdet[14].

Nordjylland

Landets største CO_2-udleder er placeret i Aalborg nær ved Nordjyllandsværket og affaldsforbrændingen Reno Nord. Hertil kommer en række mindre punktkilder i oplandet til Aalborg. Dette giver grundlag for en klynge, som vist i tabellen nedenfor. Udlederne er illustreret i Figur 18 og potentialet er vist i Tabel 5. Nordjyllandsværket er ikke medtaget i opgørelsen, da det ikke vurderes rentabelt at etablere CO_2-fangst på anlægget. Årsagen er, at ejerne, Aalborg Forsyning har meldt ud, at Nordjyllandsværkets drift udfases gradvist og ophører endeligt med udgangen af 2028.

[14] C4 er et samarbejde mellem store punktudledere og øvrige CCS-interessenter i Hovedstadsområdet: https://a-r-c.dk/c4/.

Figur 19 Overblik over punktkilder i Nordjylland. Kilde: Energistyrelsen.

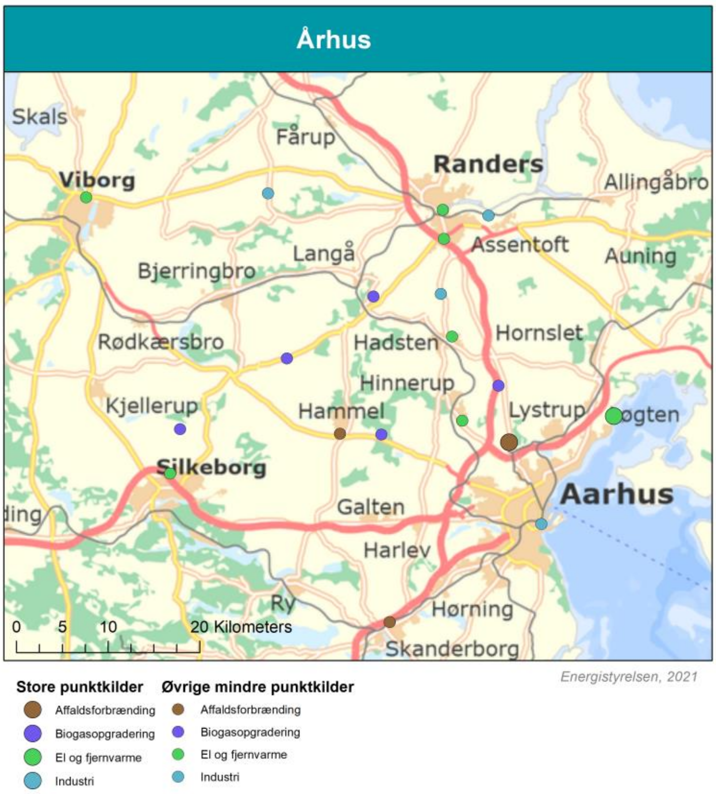
Tabel 5 Fangstpotentialer for store og små punktkilder i Nordjylland. Der er anvendt samme skæringspunkter vedr. størrelser og antal fuldlasttimer som for sektoropgørelserne i øvrigt. Udledningerne fra de enkelte virksomheder er aggregeret af hensyn til potentielt kommerciel følsomhed af oplysningerne.

	Samlede udledninger, mio. ton CO_2/år			Biogene udledninger, mio. ton CO_2/år			Fossile udledninger, mio. ton CO_2/år		
	2025	2030	2040	2025	2030	2040	2025	2030	2040
Store udledere	1,9	1,9	1,9	0,4	0,5	0,6	1,5	1,3	1,3
- Aalborg Portland									
- Reno Nord									
Øvrige mindre udledere									
- Affaldsforbrænding	0,1	0,0	0,1	0,0	0,0	0,0	0,0	0,0	0,0
- El og fjernvarme	0,0	0,1	0,1	0,0	0,1	0,1	0,0	0,0	0,0
- Industri	0,0	0,1	0,1	0,0	0,1	0,0	0,0	0,0	0,0
- Biogasopgradering	0,1	0,1	0,1	0,1	0,1	0,1	0,0	0,0	0,0
Sum	**2,1**	**2,2**	**2,3**	**0,6**	**0,8**	**0,9**	**1,6**	**1,3**	**1,4**

Århus og omegn

I Århus forventes Studstrupværket, Lisbjerg Kraftvarmeanlæg og Affaldscenter Aarhus at være i drift frem mod 2040. Studstrupværket er medtaget, selvom værket i denne opgørelse vurderes at have for få årlige fuldlasttimer i 2040 til, at CO_2-opsamling vil være rentabel og anlægget ikke forventes at være i drift efter 2040, jf. Energistyrelsens analyseforudsætninger til Energinet. Denne vurdering er dog særdeles usikker, og værket er derfor medtaget her. Det er derfor væsentligt at være opmærksom på, at eventuelle CCUS-anlæg knyttet til Studstrupværket kan medføre, at der udledes og fanges CO_2 fra anlægget som alternativt ville have væsentligt færre driftstimer eller være helt lukket. Det samme gør sig principielt gældende for andre anlæg.

Hertil kommer en række mindre anlæg i oplandet samt i Randers. Udlederne er illustreret i Figur 19 og potentialet er vist i Tabel 6.



Figur 20 Overblik over punktkilder i Aarhus og omegn. Kilde: Energistyrelsen.

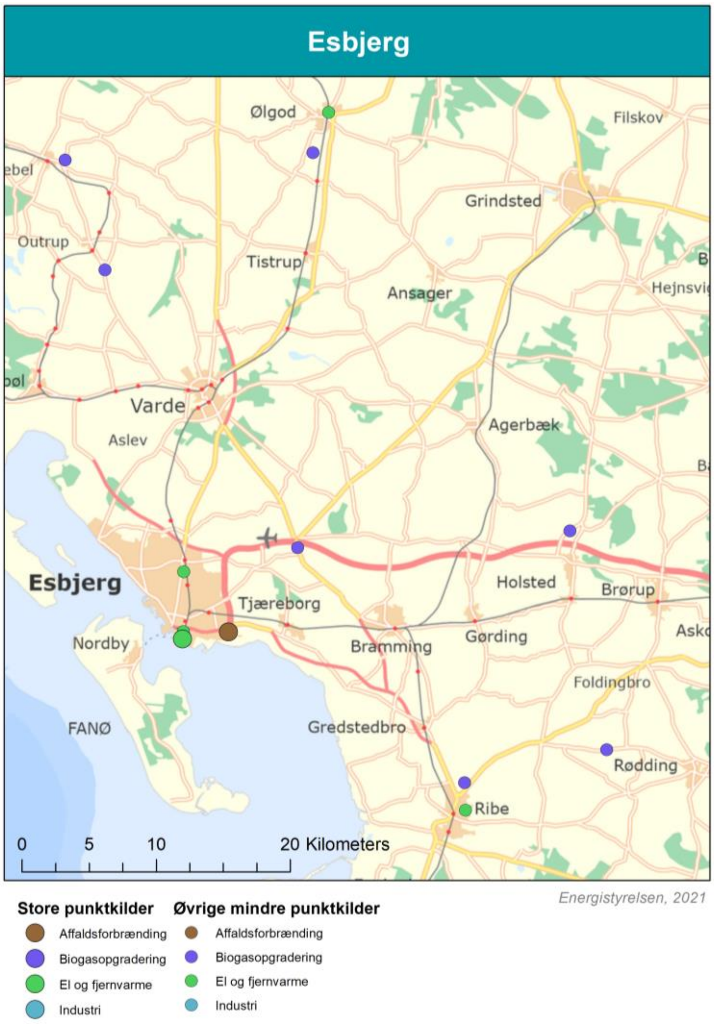
Tabel 6 Fangstpotentialer for store og små punktkilder omkring Aarhus og Randers. Der er anvendt samme skæringspunkter vedr. størrelser og antal fuldlasttimer som for sektoropgørelserne i øvrigt. Udledningerne fra de enkelte virksomheder er aggregeret af hensyn til potentielt kommerciel følsomhed af oplysningerne.

	Samlede udledninger, mio. ton CO_2/år			Biogene udledninger, mio. ton CO_2/år			Fossile udledninger, mio. ton CO_2/år		
	2025	**2030**	**2040**	**2025**	**2030**	**2040**	**2025**	**2030**	**2040**
Store udledere	1,5	0,5	0,3	1,4	0,5	0,3	0,0	0,0	0,0
- Studstrupværket									
- Lisbjerg Kraftvarmeværk									
- Affaldscenter Aarhus									
Øvrige mindre udledere									
- Affaldsforbrænding	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
- El og fjernvarme	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
- Industri	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
- Biogasopgradering	0,1	0,1	0,1	0,1	0,1	0,1	0,0	0,0	0,0
Sum	**1,6**	**0,6**	**0,4**	**1,5**	**0,6**	**0,4**	**0,0**	**0,0**	**0,0**

Noter:
[1]: Studstrupværket forventes at have for få driftstimer fremover til at være inkluderet i det samlede potentiale for CO_2-fangst i Danmark. Anlægget er dog medtaget i denne klyngeangivelse, da der ikke er konkrete udmeldinger om lukning.
[2]: Der eksisterer en produktionsvirksomhed i området, der – som følge af de generelle fremskrivninger i KF21 - antages at elektrificere sit brændselsforbrug. Der er dog ikke foretaget en virksomhedsspecifik vurdering, og dermed kan potentialet være undervurderet med ca. 50.000 ton CO2 per år.

Esbjerg

Esbjerg havn kan potentielt udgøre udskibningssted for CO_2 til lagring i Nordsøen. Samtidig ligger affaldsforbrændingen Energnist i Esbjerg, og Esbjergværket forventes erstattet bl.a. af en større biomassefyret kedel. Hertil kommer en række store biogasopgraderingsanlæg i Sydjylland mv. Udlederne er illustreret i Figur 20 og potentialet er vist i Tabel 7.



Figur 21 Overblik over punktkilder i Esbjerg og omegn. Kilde: Energistyrelsen.

Tabel 7 Fangstpotentialer for store og små punktkilder omkring Esbjerg. Der er anvendt samme skæringspunkter vedr. størrelser og antal fuldlasttimer som for sektoropgørelserne i øvrigt. Bemærk betydeligt overlap med opgørelsen for området omkring Fredericia. Udledningerne fra de enkelte virksomheder er aggregeret af hensyn til potentielt kommerciel følsomhed af oplysningerne.

	Samlede udledninger, mio. ton CO_2/år			Biogene udledninger, mio. ton CO_2/år			Fossile udledninger, mio. ton CO_2/år		
	2025	**2030**	**2040**	**2025**	**2030**	**2040**	**2025**	**2030**	**2040**
Store udledere	0,3	0,2	0,2	0,2	0,2	0,2	0,1	0,0	0,0
- Energnist, Esbjerg									
- Ny fliskedel, Esbjerg									
Øvrige mindre udledere									
- Affaldsforbrænding	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
- El og fjernvarme	0,1	0,1	0,1	0,1	0,1	0,1	0,0	0,0	0,0
- Industri	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
- Biogasopgradering	0,2	0,2	0,2	0,2	0,2	0,2	0,0	0,0	0,0
Sum	**0,5**	**0,5**	**0,5**	**0,5**	**0,5**	**0,5**	**0,1**	**0,0**	**0,0**

Fredericia og Trekantsområdet

I Trekantsområdet findes Shells raffinaderi i Fredericia, Skærbækværket og Energnists affaldsforbrænding i Kolding. Hertil kommer en række store biogasopgraderingsanlæg i Sydjylland. Bemærk, at der er overlap mellem oplandet til Esbjerg og Fredericia. Udlederne er illustreret i Figur 21 og potentialet er vist i Tabel 8. Skærbækværket er medtaget, selvom værket i denne opgørelse vurderes at have for få årlige fuldlasttimer i 2040 til, at CO_2-opsamling vil være rentabel og anlægget derfor ikke regnes med i det samlede nationale potentiale i denne analyse. Det er derfor væsentligt at være opmærksom på, at eventuelle CCUS-anlæg knyttet til Skærbækværket kan medføre, at der udledes og fanges CO_2 fra anlægget som alternativt ville have væsentligt færre driftstimer. Det samme gør sig principielt gældende for andre anlæg.

Figur 22 Overblik over punktkilder i Fredericia og omegn. Kilde: Energistyrelsen.

Tabel 8 Fangstpotentialer for store og små punktkilder omkring Fredericia og trekantsområdet. Der er anvendt samme skæringspunkter vedr. størrelser og antal fuldlasttimer som for sektoropgørelserne i øvrigt. Bemærk overlap med opgørelsen for området omkring Esbjerg. Udledningerne fra de enkelte virksomheder er aggregeret af hensyn til potentielt kommerciel følsomhed af oplysningerne.

	Samlede udledninger, mio. ton CO_2/år			Biogene udledninger, mio. ton CO_2/år			Fossile udledninger, mio. ton CO_2/år		
	2025	2030	2040	2025	2030	2040	2025	2030	2040
Store udledere	0,5	0,5	0,4	0,4	0,2	0,2	0,4	0,4	0,4
- Shell Raffinaderiet									
- Skærbækværket									
- Energnist, Kolding									
Øvrige mindre udledere									
- Affaldsforbrænding	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
- El og fjernvarme	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
- Industri	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
- Biogasopgradering	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
Sum	**0,5**	**0,5**	**0,4**	**0,4**	**0,3**	**0,2**	**0,4**	**0,4**	**0,4**

Noter:

[1]: Skærbækværket forventes at have for få driftstimer fremover til at være inkluderet i det samlede potentiale for CO_2-fangst i Danmark. Anlægget er dog medtaget i denne klyngeangivelse, da der ikke er konkrete udmeldinger om lukning.

Bilag 1 – Metode

Opgørelserne i dette notat tager udgangspunkt i Energistyrelsens Klimastatus og – Fremskrivning 2021 (herefter KF21). Dette produkt indeholder en såkaldt *frozen policy* fremskrivning af hele energisystemet – det som tidligere var kendt som Energistyrelsens basisfremskrivning. Fremskrivningen kortlægger, hvordan energisystemet forventes at udvikle sig frem til 2030 i fravær af ny politik, og anvendes således som baseline-forløb for effektvurderinger af politiske tiltag mv. Af samme årsag rækker KF21 derfor også kun frem til 2030.

Opgørelserne i denne analyse rækker frem til 2040, hvilket er nødvendigt, da de investeringer, der foretages i anlæg til CO_2-opsamling må forventes at eksistere minimum 20 år frem. Tilgangen til fremskrivningen varierer mellem de behandlede sektorer, og er beskrevet herunder.

Udledninger fra affaldsforbrænding samt fra el- og fjernvarmeproduktion i dette notat er aggregeret efter sektorer på en anden måde end i KF21. Derfor kan de opgjorte udledninger fra disse sektorer ikke genfindes direkte i KF21. Hertil kommer at rene kondensværker (elproduktion uden samtidig varmeproduktion) ikke er medtaget i denne opgørelse, da disse anlæg kun har få årlige driftstimer og derfor ikke er relevante for CO_2-fangst.

Affaldsforbrænding

Kapaciteten og produktionen i affaldsforbrændingssektoren er fremskrevet i KF21 frem til 2030, på baggrund af dels et fald i den årlige miljøgodkendte kapacitet til affaldsforbrænding på de 23 nuværende dedikerede og multifyrede affaldsforbrændingsanlæg, og dels en forventet stigning i udsortering af særligt plastaffald til genanvendelse. Udviklingen baseres derudover på forventede løbende nedlukninger af en række ældre udslidte ovnliner, samt yderligere nedlukning af kapacitet og implementering af virkemidler som følge af Klimaplan for en grøn affaldssektor og cirkulær økonomi. Fra 2030 til 2040 er udviklingen forlænget med tilsvarende frozen policy-antagelser.

El- og Fjernvarmeproduktion

Kapaciteten og produktionen i el- og fjernvarmesektoren er fremskrevet i KF21 frem til 2030 ved hjælp af modellen DH-Invest på baggrund af brændselspriser, teknologikataloger, samt gældende afgifter og regulering. Fra 2030 til 2040 er udviklingen forlænget med tilsvarende frozen policy-antagelser samt en yderligere vurdering af lukninger og erstatning af forældet kapacitet i perioden 2030 til 2040.

Industri

Industrivirksomheder repræsenteres med en enkelt undtagelse ikke separat i KF21. Opgørelsen bygger derfor på oplysninger fra kvoteregisteret for CO_2-udledninger fra de 30 største kvoteomfattede industrielle punktudledere i Danmark. Disse er fremskrevet med udviklingen i sammensætning af brændselsforbrug i delbrancher ifølge KF21, hvilket bl.a. omfatter udviklingen i aktivitetsniveau (vækstforløb) og energieffektivisering/elektrificering. Dertil indgår virksomhedsspecifikke vurderinger, som f.eks. Nordic Sugars og Rockwools omlægning til naturgas. Aalborg Portlands omlægning til naurgas er ikke en del af KF21 grundforløbet. Fremskrivningen fra 2030 til 2040 er baseret på en forlængelse af udviklingen i KF21 frem til 2040. Forlængelsen frem mod 2040 er ikke en del af den konsoliderede fremskrivning, og er derfor forbundet med væsentlig usikkerhed.

Biogasopgradering

KF21 indeholder en fremskrivning af biogasproduktionen på eksisterende anlæg med biogasopgradering frem til 2030. Disse anlæg vurderes at have en samlet produktion på omkring 28,9 PJ i 2030. Hertil kommer en yderligere produktion på ca. 11,7 PJ i 2030 fra overståede og kommende udbud, herunder udbuddene til biogas og andre grønne gasser fra 2022/2023. CO_2-udledningerne fra både eksisterende og kommende produktion er beregnet på baggrund af fangsteffektiviteter fra Energistyrelsens teknologikatalog. Frem mod 2040 fastholdes produktionen og udledningerne, dog med et mindre dyk i produktionen som følge af ophør af støtte for de ældste anlæg tidligt i perioden.

Off-shore

Olie- og gasudvinding på Nordsøen beskrives i KF21 frem til 2030. Den videre fremskrivning til 2040 udgør en forlængelse af tendensen frem mod 2030. Der er ikke foretaget en opdeling på de enkelte punktkilder i sektoren.

Afgrænsning af potentialet

Fra fremskrivningen beskrevet ovenfor opnås de samlede udledninger for de forskellige sektorer i 2025, 2030 og 2040. Ikke alle disse udledninger vil kunne opsamles i praksis. Derfor afgrænses potentialet på følgende måde:

Først og fremmest kan typiske anlæg til CO_2-fangst i dag kun opsamle omkring 90 pct. af CO_2-indholdet i røggas. Derfor nedskrives potentialerne for alle sektorer på nær biogasopgradering med 10 pct. Herefter baseres det øvre skøn for fangstpotentialet ift. punktkildernes størrelse for hver sektor, og det nedre skøn beror på en følsomhedsvurdering for de enkelte sektorer.

Omkostninger til CO_2-fangst

Omkostningerne til opsamling er beregnet for de enkelte anlæg i analysen på baggrund af den årlige CO_2-udledning og et fremskrevet eller antaget antal fuldlasttimer (for biogas antages 8.500 fuldlasttimer, for industrivirksomheder antages 7.000 fuldlasttimer, jf. dog nedenfor. For el- og fjernvarmeproduktion samt affaldsforbrænding er den årlige driftstid fremskrevet som i KF21.
Der tages udgangspunkt i Energistyrelsens teknologikatalog mht. fangstteknologier samt en række antagelser, bl.a. mht. rente, el- og varmepriser mv. På den baggrund beregnes omkostninger til etablering, drift og vedligehold (fast og variabel) samt energitab på anlægget og anvendelse af inputenergi.

Energiinput og -tab

Fangst af CO_2 fra punktkilder anvender inputenergi i form af mellemtemperatur varme. På kraftvarmeanlæg som biomasseanlæg og affaldsforbrænding forventes dette input at komme fra lavtryksdampturbinen. Dette sænker elproduktionen på anlægget markant, og der vurderes at være tale om tab af el- og varmeproduktion på hhv. 15-50 pct. og 15-30 pct. afhængig af typen af anlæg mv. Der er indregnet skøn for omkostningerne til dette. Ændringen i output fra anlægget vurderes dog også at kunne få betydning for anlæggenes driftsmønster, hvilket potentielt kan medføre yderligere tab. Disse er ikke medregnet i denne opgørelse, hvilket betyder, at estimaterne skal læses konservativt – særligt mht. kraftvarmeanlæg og affaldsforbrænding.

Det antages i øvrigt, at overskudsvarmen fra fangstanlægget ikke udnyttes til fjernvarme, hvilket vurderes at ville være tilfældet nogle steder. Dette rykker dog ikke markant ved resultatet.

Industrianlæg

Der er begrænset visen om driften af industrianlæg og meget stor usikkerhed om fremskrivningen af denne type anlæg. Opgørelsen omfatter 10 virksomheder, som alle udgøres af enten fødevarevirksomheder eller energiintensive virksomheder (stål, cement, raffinaderi, tegl). Alle disse virksomheder vurderes at drifte i skiftehold og dermed have høje antal af fuldlasttimer (7.000). Undtagelsen er en indeholdt sukkerfabrik, som driftes i årlige kampagner. Her antages 2.500 årlige fuldlasttimer. Hertil kommer, at industrivirksomheder vurderes, at have betydeligt højere forrentningskrav end de fleste aktører i forsyningssektoren. Der er således regnet med interne forrentningskrav (WACC) på 10 pct. for industrivirksomheder i modsætning til de 3,5 pct. der antages for affaldsforbrænding, el- og fjernvarmeproduktion og biogasopgradering.

Klima-, Energi- og Forsyningsministeriet

Oversigt over fuldskala CCS-anlæg

Center
Center for Klimaneutralt Danmark

Team
Viden, forskning og omstilling

Dato
27. oktober 2021

J nr. XXX

/ JASHA

Baggrund
Der findes i dag ca. 27 fuldskala CCS projekter i kommerciel drift hvoraf ét er midlertidigt lukket. Nedenfor fremgår 4 fuldskala-CCS-projekter uden Enhanced Oil Recovery (EOR). Derudover er der en lang række yderligere projekter i udviklings- og demonstrationsfasen.

Tabel 1 Oversigt over fuldskala-CCS projekter (ekskl. EOR projekter)

Navn	Land	Produktion/år	Beskrivelse	Lagring
Sleipner	Norge	Naturgas opgradering 1996	Separation af CO_2 fra naturgas. Fangstanlægget er placeret på platform offshore. CO_2-fangst sker vha. aminbaseret metode (MDEA) med en kapacitet på 0,85 Mtpa. CO_2 injiceres i et off-shore geologisk sandstenslager ved Sleipner, ud for Norge I alt 17 Mt er injiceret til lageret siden 1996. Lager: salin sandstens reservoir på 1.000m dybde.	Geologisk lagring
Snøvit	Norge	Naturgas opgradering 2008	Separation af CO_2 fra naturgas. Fangstanlægget er placeret på øen Melkøya, hvor der sker en opgradering af gas fra offshore installation. CO_2-fangst sker vha. aminbaseret metode med en kapacitet på 0,7 Mtpa. CO_2 injiceres i et off-shore geologisk lager ved Snøhvit feltet. Trans-port sker i rør. I alt 4 Mt er injiceret til lageret siden 2008. Lager: salin sandstens reservoir, dybde 2.550m	Geologisk lagring
Questt, Shell	Canada	Hydrogen produktion 2015	Separation af CO_2 fra HMU (hydrogen manufacturing unit) til produktion af hydrogen. CO_2-fangst sker via ADIP-X processen (amin absorption) med en kapacitet på 1 Mtpa. CO_2 transporteres via rørledning til geologisk lagring onshore. I sommeren 2020 er 5 mill. ton injiceret.	Geologisk lagring
Gorgon	Australien	Naturgas opgradering 2019	Separation af CO_2 fra naturgas. CO_2-fangst med en kapacitet på 3,4-4 Mtpa. CO_2 er lagret i et onshore lager på Barrow Island. Transport til lager sker i rør. Lager: salin sandstens reservoir, dybde 2.300m	Geologisk lagring

Kilde: COWI, 2021. CCS – Internationale erfaringer – sikkerhed, natur og miljø: 2021. Danmark.
Kilde: Global CCS Institute, 2021. The Global Status of CCS: 2021. Australia