# CCUS Infrastructure in Northern Jutland

*Investigating the Feasibility of Implementation of CCUS Infrastructure*

Aalborg University
Sustainable Energy Planning and Management

Master Thesis

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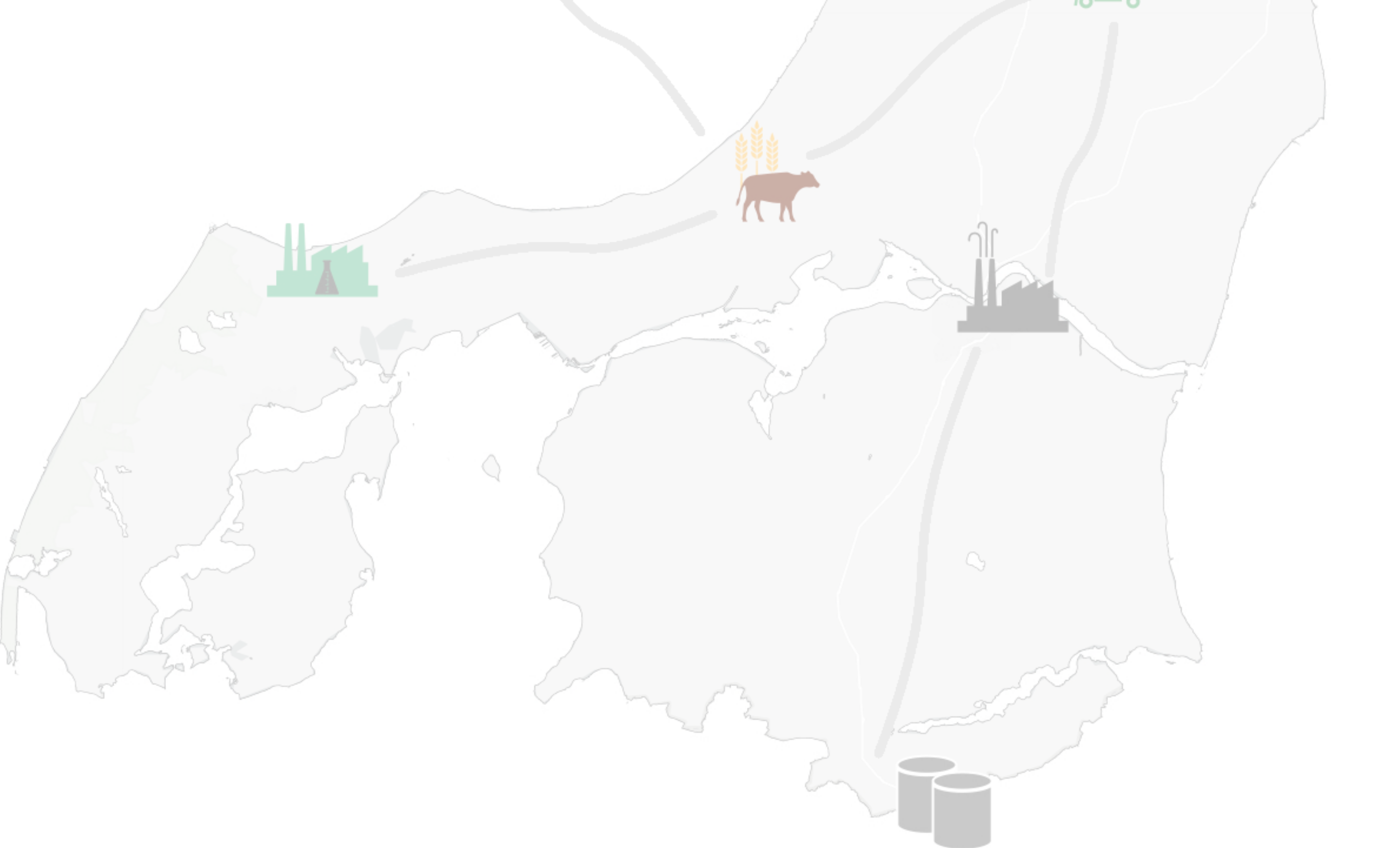

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**Abstract:**

$CO_2$ will in the future be captured from both fossil and biogenic point sources and be used for production of e-fuels or permanently stored underground in order to reduce carbon emissions. This study investigates the possibilities of planning for and implementing a Carbon Capture, Utilization and Storage (CCUS) infrastructure in Northern Jutland, in order to determine how a specific infrastructure including carbon capture, transport, storage and utilization of $CO_2$ can be arranged and if it is economically feasible to do so. Furthermore, the study investigates what initiatives that are needed for the implementation of such an infrastructure to be fulfilled. Geographical Information Systems (GIS) is used to design different routes for the network between point sources and sinks, and socio-economic evaluation is used to determine the feasibility of the network. In total, three different scenarios are investigated, that include different capacities of point sources. It is found that a scenario with point sources that emit > 40,000 ton $CO_2$ a year give the highest socio-economic value, and have the lowest costs for every ton of $CO_2$ that is captured, transported and used or stored. Through a sensitivity analysis, it is evident that the price of which $CO_2$ emission allowances are sold at, have a high influence on the economic feasibility of these scenarios. Through interviews with actors of the CCUS value chain, it is found that the organizational aspect carries a high value in the planning and implementation of CCUS infrastructure, and that several actors rely on the state to aid financially through funds and subsidies.

# Signature

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# Preface 1

This master thesis was created during the 4th semester at the Master of Sustainable Energy Planning & Management at Aalborg University.
A thank you is directed to supervisor Steffen Nielsen for guidance throughout the period of writing the thesis and to all the interviewees who took time to participate.

**Reading guide**
The references in this report are presented via the Harvard Reference System where the citation commence with the name of the author and thereby the year of publication. The comprehensive list of sources is included in the bibliography in the end of the report. The figures that are included in the report are given numbers, ie. 4.2, representing that the figure is the second figure in chapter 4. The same method is used for tables.
The report consists of chapters and subsections dividing the topics of the report. The appendix is attached as the final part of the report. It is recommended that the report is read in a chronological order.

The following appendices are attached in the report:

- Input for the economic evaluation in appendix A
- The interview guide used as guideline for interviews in appendix A.11
- Overview of interview responses in appendix A.12

The following appendices are attached externally:

- The excel file utilized in the evaluation of economic feasibility of CCUS infrastructure
- Audio files of the eight conducted interviews

**Abbreviations**

| | |
|---|---|
| **CC** | Carbon Capture |
| **CCS** | Carbon Capture & Storage |
| **CCU** | Carbon Capture & Utilization |
| **CCUS** | Carbon Capture, Utilizations & Storage |
| $CO_2$ | Carbon Dioxide |
| **NPV** | Net Present Value |

# Danish Summary 2

$CO_2$-fangst og udnyttelse (CCUS) kan bidrage til den grønne omstilling. Ved at udnytte $CO_2$ til producering af e-fuels såsom e-methanol og Sustainable Aviation Fuel (SAF), er $CO_2$ gået fra at være et affaldsstof der skal undgås, til at være et vigtigt element i produktion af bæredygtige brændsler til fremtidens transport. Den $CO_2$ der ikke skal bruges til e-fuel produktion, kan lagres permanent i undergrunden, for at reducere udledningen af $CO_2$.
På nuværende tidspunkt bliver CCUS undersøgt og udviklet på verdensplan, gennem forskellige projekter. I disse projekter påpeges det, at lokale omstændigheder har stor indvirkning på den tekniske mulighed og de økonomiske omkostninger ved CCUS projekter. Lokale omstændigheder omfatter både terræn og økonomiske forudsætninger, samt lokal regulering, lovgivning og strategier for CCUS.
I Danmark har regeringen offentliggjort aftalen "En køreplan for fangst, transport og lagring af $CO_2$". I denne indgår planer for forskellige tiltag såsom økonomiske puljer, samt initiativer til forskellige samarbejder der kan være med til at sætte kursen for udviklingen af CCUS i Danmark. Som en del af dette har bl.a. et klyngesamarbejde i Nordjylland, overordnet undersøgt mulighederne for at transportere $CO_2$ på tværs af Nordjylland.

På baggrund af dette, udspringer følgende problemformulering:

*Hvordan kan en CCUS infrastruktur i Nordjylland blive planlagt, baseret på planlægningsudsigter, $CO_2$-tilgængelighed samt rumlig og økonomiske muligheder?*

Problemformuleringen sætter udgangspunktet for, at potentialet for en CCUS infrastruktur bliver undersøgt med en holistisk tilgang, hvor både økonomi, teknik og rumlige udfordringer undersøges.

Undersøgelsen af dette tager udgangspunkt i at dække alle aspekter af teknologidefinitionen, der indebærer aspekterne; Teknik, Produkt, Organisation, Viden og Profit. Dette indtænkes for at sikre en helhedsorienteret undersøgelse af CCUS som en teknologi der både indebærer fangst, transport og lagring af $CO_2$. Ved at bruge dette aspekt, involveres også konceptet "choice awareness", der understreger at undersøgelse af forskellige tekniske scenarier skal udføres så de kan sammenlignes og at der gøres opmærksomhed på, at der kan tages et valg, uden at ét scenarie er forfordelt på forhånd.

Til at udføre analyserne i rapporten benyttes forskellige metoder. Den rumlige analyse undersøges via geografisk informationsteknologi (GIS), hvorved softwaren ArcGIS Pro benyttes til at producere forskellige ruter mellem $CO_2$ punktkilder og udnyttelse og lagring i Nordjylland. Baseret på tre forskellige udgaver af hvilke punktkilder der indgår i infrastrukturen, produceres tre forskellige ruter i et samlet netværk. Scenarierne er som følger:

- A – Punktkilder > 1,000 ton $CO_2$/år, baseret på nuværende udledninger
- B – Punktkilder > 40,000 ton $CO_2$/år, baseret på nuværende udledninger
- C – Punktkilder > 10,000 ton $CO_2$/år, baseret på udledninger i 2045

Ruterne har fællestræk i og med at alle lokationer til udnyttelse og lagring er ens i hvert scenarie. Længderne på ruterne og mængden af $CO_2$ der sendes på strækningerne, benyttes til at bestemme om $CO_2$'en skal sendes med lastbil eller hvilken størrelse rør der skal benyttes til at transportere det.

På baggrund af den rumlige analyse, benyttes en samfundsøkonomisk analysemetode til at bestemme de samfundsøkonomiske omkostninger ved at udregne nettonutidsværdien for alle tre scenarier. Omkostningerne for investering, drift & vedligehold samt den mistede $CO_2$-afgift og salg af $CO_2$ kvoter, indgår i den samfundsøkonomiske vurdering, der viser at det scenarie hvor der er færre større punktkilder inkluderet har den bedste samfundsøkonomiske værdi. Grunden til dette, er at selvom der er færre punktkilder, udleder de medtagede punktkilder stadig størstedelen af den samlede mængde $CO_2$ der udledes af alle punktkilder i Nordjylland. Dette vil sige, at på trods af, at der samlet fanges mindre $CO_2$ i dette scenarie, vil de mindskede investeringsomkostninger opveje omkostningen, så salget af $CO_2$-kvoter overstiger omkostningerne til investering og drift & vedligehold. Det kan ses at prisen for $CO_2$-kvoter har stor indflydelse på, hvornår et scenarie er muligt, siden det er den eneste indtægtskilde benyttet i den samfundsøkonomiske vurdering. Ydermere undersøges den årlige specifikke omkostning pr. ton $CO_2$ for hvert scenarie, hvori de samfundsøkonomiske omstændigheder ikke indgår. I dette tilfælde har scenarie med færrest punktkilder også den laveste omkostning.

Ydermere er interviews benyttet som metode, til yderligere at inkludere alle elementer af teknologibegrebet og til at undersøge de forskellige forventninger til implementeringen af en CCUS infrastruktur.
I løbet af otte interviews, blev størstedelen af værdikæden for CCUS infrastruktur dækket fra punktkilder til transport og udnyttelse af $CO_2$. Resultatet af denne undersøgelse er, at der særligt i oranisationsaspektet af teknologien, er et ønske om strukturering af, hvordan regler, standarder og lovgivning for transport og benyttelse af $CO_2$ vil se ud. Interviewpersonerne var hovedsageligt enige om, at denne strukturering skal ske fra statens side. Ydermere blev det efterspurgt at staten yder økonomisk støtte i højere grad end de puljer der er udbudt på nuværende tidspunkt, da det stadig ikke er økonomisk attraktivt for virksomhederne at investere i CCUS infrastruktur.

I dette speciale kan det konkluderes, at det er muligt at opnå en samfundsøkonomisk fordelagtig CCUS infrastruktur ved hjælp af de benyttede metoder, og at den specifikke rute kan optimeres i forhold til, hvilke punktkilder og lokationer til lager og udnyttelse der medtages i det samlede netværk. Ydermere er det vist, at der fra værdikædens side er et ønske om, at staten igangsætter yderligere tiltag der kan starte implementeringen af en CCUS infrastruktur.

# Table of content

# Introduction 3

$CO_2$ has been known as a by-product of industrialization with negative effects to follow in the role of climate change. This is expressed through the London Protocol that prohibits transboundary dumping of waste on maritime areas, where $CO_2$ is perceived as a matter of waste [International Maritime Organization, 2019]. This perception of $CO_2$ is however beginning to change. $CO_2$ is facing a future as being a sought-after commodity. This is due to the race towards reducing $CO_2$ emissions where storage of fossil $CO_2$ play an important role in the energy transition as a carbon emission reduction method, that is necessary for the decarbonization of agricultural, and other industrial sectors [Lund et al., 2021]. $CO_2$ will be utilized to produce e-fuels to substitute the fossil fuels in hard-to-abate sectors ie. the maritime transport [Agarwal and Valera, 2022].
Yet, the topic of $CO_2$ is complex and there are several complications to solve. According to IPCC [2022], $CO_2$ emissions from the industry and the use of fossil fuels are still rising, and a means to reduce these in e.g. the power sector, are to use low-carbon fuels, decommission fossil fuel plants, and to incorporate Carbon Capture and Storage (CCS) in existing plants [IPCC, 2022]. When $CO_2$ is captured and stored underground or re-used for other purposes such as e-fuel production, it is defined as carbon capture, utilization and storage (CCUS) [The Danish Energy Agency, 2021e].

The concept of CCUS is relevant since it plays a role in the overall energy transition [González Plaza, 2022]. First of all, investigating where it is feasible to implement carbon capture plants is a step towards a CCUS infrastucture. This potential is investigated by ie. The Danish Energy Agency [2023a] who verifies the possibility of carbon capture at various point sources in Denmark, but also stress the uncertainties of the results that can be impacted by local circumstances. The next part of the CCUS value chain is to decide where to transport the $CO_2$. There are plans for storage and utilization across Denmark and several projects have already commenced [Project Greensand, n.d.; Green Hub Denmark, 2022; The Danish Board of Business Development, 2022a]. This highlights the need for a holistic view on the planning of CCUS and an issue thereof is the transport between the source of the $CO_2$ and the site for storage or utilization.
Having a $CO_2$ infrastructure is a vital element of the security of supply for this new type of infrastructure that CCUS is foreseen to become. Consequently, planning for the CCUS infrastructure and the steps within is a topic to investigate since several aspects, such as point sources, modes of transport and sinks are uncertain and reliant of each other.

This report seeks to investigate CCUS and the feasibility of a potential infrastructure in Northern Jutland. The feasibility of a CCUS infrastructure involves a spatial and economic analysis, and an evaluation of $CO_2$ availability is included in this. Additionally, the implementation process and planning prospect for CCUS are explored.

# Context of the Research Topic 4

This chapter describes the basic understandings of CCUS and how this fits with the Danish context of the energy transition. Furthermore, the chapter describes the current state of the art within research on this topic, giving an understanding of where new research can have a contributing element. Additionally, the local context of CCUS is problematized showing that there are several elements to consider when planning for a CCUS infrastructure in Denmark.

## 4.1 Carbon Capture, Utilization and Storage

The $CO_2$ that is captured via carbon capture, can be used for further refinement through Power-to-X (PtX), by combining it with hydrogen from electrolysis [The Danish Energy Agency, 2017]. This process is used to produce e-fuels, such as methanol or Dimethyl Ether (DME) [The Danish Energy Agency, 2021e]. The $CO_2$ can also be compressed and stored underground, to inhibit the emission to the atmosphere [The Danish Energy Agency, 2021e]. The storages can exist onshore, nearshore or offshore in depleted oil or gas fields [The Danish Energy Agency, 2021e]. In figure 4.1, the value chain of how the $CO_2$ can be utilized or stored is illustrated.

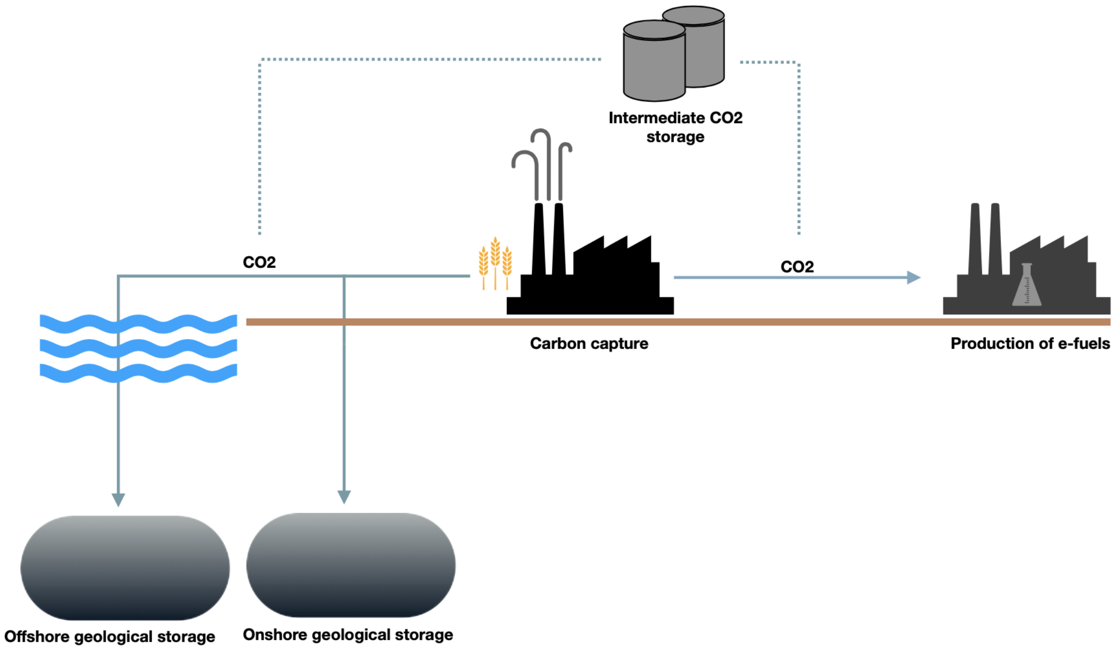


**Figure 4.1.** Overview of the possible CCUS value chains.

The figure shows how $CO_2$ is captured from a facility, such as a power plant, and transported via e.g. trucks, pipelines or ship to an underground storage, which can both exist onshore or offshore, as well as transported to a PtX facility where the $CO_2$ is further refined to produce fuels. In between the transportation of the $CO_2$, it can be stored in an intermediate storage, to be utilized or transported at a different time [The Danish Energy Agency, 2021e]. The production of e-fuels is not investigated further in this report but are considered to be a $CO_2$ sink along with storage.

The carbon can be captured by using different technologies, eg. amine post combustion, oxy-fuel combustion, or Direct Air Capture (DAC) technologies, depending on the type of source of $CO_2$ and where it can be captured [The Danish Energy Agency, 2021e]. When utilizing Carbon Capture, $CO_2$ can be captured from all $CO_2$ sources such as fossil-using CHP plants or biogas plants – where the latter is defined as biogenic $CO_2$, meaning a "renewable" $CO_2$, because the input is considered sustainable [International Energy Agency, 2023]. Since the use of fossil fuels for energy production is being phased out, some of the current point sources of $CO_2$ from fossil fuel based energy plants, might be reduced or disappear in the future, which means that the $CO_2$ as a fuel or product can become less available over time. When the $CO_2$ is used to produce renewable e-fuels, the sources of $CO_2$ should be biogenic and not from fossil fuel using plants to ensure a sustainable fuel [Methanol Institute, n.d.].

Since the source of $CO_2$ and the place where it can be utilized or stored is not necessarily in the same location, it needs to be transported in order to reach its destination. The $CO_2$ can be transported via roads, ships or via pipes [The Danish Energy Agency, 2021e]. When $CO_2$ is transported it is either compressed to a high pressure gas for pipeline transportation or liquefied where it can be transported by trucks and ships. Truck transport is only considered advantageous for smaller quantities of $CO_2$ [The Danish Energy Agency, 2021e]. There exists both long-term storage and intermediate storage - where the $CO_2$ is stored short-term either at the capture or storage site [The Danish Energy Agency, 2021e]. The long-term storage is geological storage. If these are placed offshore, these can either be connected to the $CO_2$ source by ship transport or offshore pipelines [The Danish Energy Agency, 2021e]. The intermediate storage can eg. support the transport of $CO_2$ from sources that aren't connected by pipeline directly to the long-term storage [The Danish Energy Agency, 2021e].

## 4.2 State of The Art Related to CCUS Infrastructure

The purpose of this section is to state the current developments and findings of the knowledge base regarding CCUS and to introduce main elements of articles on the matter. This section is used to present the general knowledge of this topic, which aids to set the direction of this report's analyses. The knowledge base entails aspects such as technology development for carbon capture, mode of transportation, infrastructure for $CO_2$ and implementation of the technologies involved. The main focus is on the infrastructure developments of $CO_2$ transportation and the relation to the carbon capture sites.

*Technology development*
The current literature is focused on the technological development of CCUS which includes

elements such as technological readiness level and the barriers and opportunities this poses for the future development [Jarvis and Samsatli, 2018]. Several articles focus on the role that $CO_2$ plays in connection with conversion technologies, to produce chemicals and mainly to produce methanol sustainably [Spadaro et al., 2020; Gabrielli et al., 2020; Arnaiz del Pozo et al., 2022].

Middleton et al. [2020] argues that selecting carbon capture sites for CCS infrastructure should be based on cost-effective arguments and in a structured way. Han and Lee [2012] further describes a model of how to determine the amount of $CO_2$ to capture in an overall perspective of minimizing costs related to the whole infrastructure. Becattini et al. [2022] investigates several scenarios with variation in location of capture sites and sizes and underlines that this is important for finding the optimal and cost-effective route and system setup for a CCS-infrastructure.

*Economic considerations*

Arnaiz del Pozo et al. [2022] focus on the economics of the pathways towards producing methanol and state that DAC (Direct Air Capture) and $CO_2$ utilization is still more costly when utilized together with water electrolysis compared to using the natural gas production approach, which is not sustainable. Furthermore, the DAC pathway requires strong policy support to become cost-competitive. This pins the argument that the general development of CCUS is still under pressure to reduce costs.

Calculating cost is also an aspect of investigation for a case study of $CO_2$ infrastructure in connection with solar energy as energy source to produce e-fuels in South and Central Europe. The exact route of the $CO_2$ pipeline is however not studied [Pantoleontos et al., 2021]. Tsongidis et al. [2019] narrows the same scope of solar energy with $CO_2$ point sources to sinks to consider $CO_2$ pipeline routing in Greece and finds expenditures for the conversion to methanol and that this is benefitted by a feed-in-tariff.

Cost seems to be a general theme when estimating the feasibility of CCU infrastructure in Europe, and it is furthermore found that a general technical unit cost of €8.6 per ton $CO_2$ could cover compression, transport and storage in a case of the Netherlands and depleted offshore infrastructure [Wildenborg et al., 2022]. Even though this price excludes some items in the calculations it is still a relative reasonable cost compared to the €14-17 per ton $CO_2$ found by Nie et al. [2021]. Becattini et al. [2022] found that pipeline cost is the largest contributor to cost of CCS, followed by capture costs and lastly storage costs that only has a minor role in terms of cost.

Utilizing existing infrastructure and retrofitting this to support an implementation of a $CO_2$ infrastructure by mapping out a carbon cluster is also the case of a Scottish study [Brownsort et al., 2016]. This study highlights that utilizing the existing infrastructure helps to reduce the costs and that the proximity of $CO_2$ point sources to the pipeline is an element to consider.

*Investigation of infrastructure for $CO_2$*

A case study of the north-central US investigates pipeline routes for $CO_2$ utilizing GIS together with analytical hierarchy process to identify regions with the highest potential for pipeline routing [Balaji and Rabiei, 2021]. This potential is expressed by a percentage and not an exact route.

Investigation of former $CO_2$ pipeline projects across the world found drivers of costs, public perception, etc. that shows this infrastructure is different in terms of the property of the $CO_2$ that differentiates the pipeline from others such as natural gas pipelines [Noothout et al., 2014]. This difference is important since there is less experience with $CO_2$ pipelines, which causes the projects of $CO_2$ pipelines to also differentiate between each other. However, the projects in the US, where ~7,000 km of $CO_2$ pipeline is in operation, which is the highest fraction of $CO_2$ pipelines in the world, prove a good example for future projects as there is more experience, especially with environmental permitting [Noothout et al., 2014].

According to a study by Neele et al. [2013] investigating the roadmap towards a CCS transport infrastructure in Europe, it is important to have strategic plans and political willingness to increase the feasibility of this type of new infrastructure. This is a part of minimizing risks of the investment of the infrastructure and capture plants as well as increasing the incentives to invest from private actors. Furthermore, it is essential to have plans that clearly outline the potential of the infrastructure such as the capacities of storage and pipeline routing. This is also supported by Mikunda et al. [2011] who highlights the importance of the legislation for new infrastructure to fit with current legislation.

A study by van den Broek et al. [2013] finds potential CCS infrastructure by combining GIS and partial equilibrium optimization modelling in the context of Spain, Portugal, Morocco. Results were held against local stakeholders, and their input were used to optimize the model, resulting in a new infrastructure suggestion. The paper found that, trying to follow the existing natural gas network and laying the route of the pipelines along the natural gas grid and following the feedback from the stakeholders had a big impact on the resulting infrastructure alleviating some of the obstacles in the terrain in the countries.

An aspect that has not been considered in the research of $CO_2$ infrastructure is the relation, interconnection and synergies of a potential $CO_2$ infrastructure and the existing natural gas grid.

*View on the general development of CCUS*

The International Energy Agency (IEA) has reviewed the CCUS development and management and the derivatives thereof. The IEA explains the importance of storage opportunities of $CO_2$ and the role it plays in the energy transition but also problematizes the need for investment, as technology development has proved to be ready for this [IEA, 2022a]. Furthermore, the IEA highlight $CO_2$ pipelines as an important step in the energy transition value chain and categorizes pipelines as having a 'very high' importance for net-zero emissions [IEA, 2023].

Pipeline is the least cost heavy mode of transportation for longer distances and quantities onshore and for some distances also offshore [IEA, 2021]. For shorter distances and quantities truck or rail is a viable option [IEA, 2021]. It is not stated what "longer" distances covers and the fact that the main experiences with $CO_2$ pipelines is from the US, highlights that investigating local examples of this is necessary. Becattini et al. [2022] states that pipeline is the most optimal solution for $CO_2$ amounts above 1.5 Mt/year, but also stress the factor of time horizon to be considered.

The potential capacity for storage has to follow the infrastructure development as well according to IEA [2022b]. Furthermore, the plans for $CO_2$ capture show a higher capacity than the plans for $CO_2$ storage, which further highlights that there is a mis-alignment

between the elements of CCUS planning.
Some of the main points of this section are:

- Policy support is essential for CCUS development
- Local circumstances need to be investigated for a successful CCUS infrastructure
- The price of the infrastructure differentiates
- There is an issue of deciding on the transport between point sources and sinks

The state of the art that is experienced internationally need to be placed on a local scale to investigate the state of CCUS development.

## 4.3 Context for CCUS in Denmark

In Denmark, the Danish Government has committed itself through legislation to reach a goal of GHG emission reductions of 70% in 2030, compared to the emissions in 1990, and to become 100 % climate neutral in 2050, which has subsequently been changed to 2045 [The Danish Ministry of Climate, Energy and Utilities, 2021b; The Danish Government, 2022]. The Act has been made to commit the country to reaching the goals set in the Paris Agreement to reduce the temperatures rising as an effect of GHG emissions [The Danish Ministry of Climate, Energy and Utilities, 2021b].

In the Danish Government's climate agreement for energy and industry, it is determined that Power-to-X and capture of $CO_2$ will be a part of the future Danish energy system to contribute to reducing emissions in the sectors where the conversion from fossil fuels is the most difficult [Socialdemokratiet et al., 2020]. The The Danish Ministry of Climate, Energy and Utilities [2021c] has developed a strategy for CCUS in Denmark that firstly focus on establishing capture and storage of $CO_2$ until 2025 and following expanding to utilization of $CO_2$ as well. This strategy also includes descriptions of what should be changed or added to current legislation in order to mobilize the application of CCUS in Denmark [The Danish Ministry of Climate, Energy and Utilities, 2021c]. Therefore, a financial pool will be given from 2024 to support and advance the technologies that support capture, utilization and storage of $CO_2$ [Socialdemokratiet et al., 2020]. Currently, there is one pilot project of storing $CO_2$ in Denmark, in a depleted oil field in The North Sea [Project Greensand, n.d.]. Furthermore, there has been made investigations of certain other areas based on their geological conditions, to determine their suitability as storage for $CO_2$, both on-, near-, and offshore [The Danish Energy Agency, n.d.a]. The Danish Ministry of Climate, Energy and Utilities has made a declaration, that enables projects for $CO_2$ storage under 100 kT onshore and nearshore in Denmark [The Danish Ministry of Climate, Energy and Utilities, 2022]. The storage is meant for research to test new processes and when the permit for the project is given, it is valid for up to two years [The Danish Ministry of Climate, Energy and Utilities, 2022]. The areas for this are shown in figure 4.2. Offshore, two projects have received permits for $CO_2$ storage in the North Sea, that are placed in depleted oil- and gas fields [The Danish Ministry of Climate, Energy and Utilities, 2023].


**Figure 4.2.** The areas where onshore and nearshore $CO_2$ storages possibly can be placed [Rambøll, 2022].

GEUS, who perform geological investigations for Denmark and Greenland estimates that the Danish underground has a capacity for storing $CO_2$, that is 400-700 times larger than Denmark's total $CO_2$-emissions currently [The Danish Energy Agency, n.d.a]. To compare, Denmark's total equivalent $CO_2$ emission in 2021 was 44 million ton [Statistics Denmark, n.d.].

The The Danish Energy Agency [2023a] has published "Point sources to $CO_2$ - Potential for CCS and CCU". The report states that there is a higher potential of capturing $CO_2$ than previously estimated. The The Danish Energy Agency [2023a] utilizes different assumptions which poses questions to the total potential of CC and which sources are relevant to consider. They utilize a lower threshold of 50,000 ton $CO_2$ per year per plant (point source) and a lower threshold of 2,500 full load hours per capture plant. The analysis from the The Danish Energy Agency [2023a] states that the cost does not increase significantly if the threshold is lowered indicating that more point sources could

be included and that this is an aspect for investigation.
It is clear that the subject of CC in a Danish context is under development and this leaves room for further research of the potential and infrastructure of CCUS.

### 4.3.1 Current Research Projects in Denmark

Other than GEUS and DEA there are several other research projects looking into CCUS. The Marco Polo Project (Methanol Availability Readiness Cost Operationality for Port Logistics) investigates the transition of Hanstholm and Frederikshavn ports to a methanol hub for the fishery and ferry transport [Energy Cluster Denmark, 2022]. The project looks into the aspects of the infrastructure required to construct at the ports. Included is the handling of $CO_2$, business models of the use of methanol on the routes and fire- and regulatory requirements. The project ends in August 2023 and thus marks one year of research and has been funded by EU-REACT with 3.4 million DKK which is supported through "Denmark's Board of Business Advancement" [The Danish Business Authority, 2022].
Denmark's Board of Business Advancement also supports another project in Northern Jutland with 92 million DKK from the EU-REACT fund [The Danish Board of Business Development, 2022a]. This is the "CO2 Vision" project which is a business beacon researching capture, storage and application of $CO_2$ and behind the beacon stands different public institutions and 27 companies [The Danish Board of Business Development, 2022b]. The beacon includes different projects which will demonstrate the CCUS infrastructure in Northern Jutland. The project runs over a period of one and a half years [The Danish Board of Business Development, 2022a].
The CCUS cluster in Northern Jutland was appointed in 2022 by the Danish Ministry of Climate, Energy and Utilities [Green Hub Denmark, 2022]. Green Hub Denmark [2022] produced the report "CCUS Cluster Northern Jutland" that gathers recommendations towards a $CO_2$ economy and infrastructure in Northern Jutland and captures the knowledge of this topic provided by several actors. The report shows a potential $CO_2$ network in different municipalities in Northern Jutland based on point sources and potential PtX projects and investigates aspects such as capital expenditures, barriers to implementation and ownership of the network. The findings of the network for $CO_2$ transport is illustrated on figure 4.3.

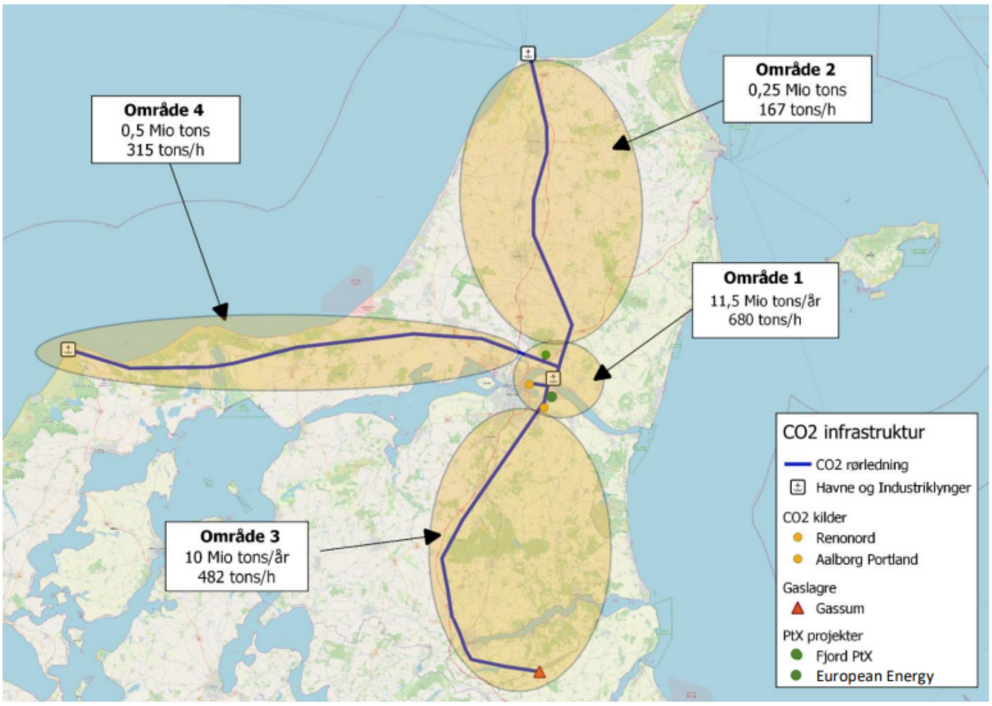


**Figure 4.3.** CO2 infrastructure in Northern Jutland as proposed by Green Hub Denmark [2022].

The routing of the pipes are on an early stage and does not represent a final suggestion of the pipeline network.
The aforementioned research projects are both set in Northern Jutland. One of the aspects that highlights Northern Jutland as a test bed or research area is the high amount of relevant infrastructure to support CCUS development. This infrastructure entails the relative amount of $CO_2$ that is possible to capture in the region. This is based on both the largest industrial emitter of $CO_2$ – Aalborg Portland – and the amount of biogas [The Danish Gas Technology Centre, 2021]. The western part of Denmark is generally known for the higher concentration of livestock that results in higher potential for biogas production [The Danish Nature Agency, 2014]. The livestock concentration in Northern Jutland is higher compared to the rest of the country and the amount of biogas plants is also on a general high level [The Danish Energy Agency, 2023b].

## 4.4 Partial Conclusion

CCUS is needed to supplement the expansion of renewable energy technologies that are being developed [IPCC, 2022] . This chapter has given an introduction to CCUS as a technology and a means to reduce $CO_2$ emissions to the atmosphere and thereby try to mitigate further climate changes in the future. The way that CCUS does this, is by capturing $CO_2$ from the air, flue gasses or from biogas upgrading and using it in a PtX facility where it can be upgraded to e-fuel, or stored in an underground storage either offshore or onshore. The challenge that exist in this value chain, is that the sources of $CO_2$ often are not placed where the $CO_2$ end use will be. Therefore, it is essential to look into the way the $CO_2$ can be transported from point source to sink.

There are different options for transport of $CO_2$ – road, rail, shipping or pipelines. According to the IEA [2023], pipelines are the most effective means of transportation for $CO_2$ and is a large part of the $CO_2$ value chain. For a number of locations, the optimal transportation routes have been found, underlining the importance of eg. local terrain and existing pipelines. As the highest fraction of $CO_2$ pipelines are located in the US, there have been several projects investigating optimal routes for $CO_2$ pipelines locally in the US. Furthermore, projects have also been done to investigate possible pipeline routes on a European scale in specific countries. This indicates that investigating pipeline conditions locally are essential to produce a useful result. Currently, many aspects of the CCUS technology, and the following economic and planning aspects, are being investigated in order to determine how the technology should be incorporated in the energy sector.

On a geographical smaller scale, in Denmark, there are also plans to establish CCUS technologies. These plans are set to aid in following the Climate Law, where Denmark should reduce its emissions by 70% in 2030 and 100 % in 2045. Currently, the Danish Ministry for Climate, Energy and Utilities is producing a strategy for CCS in Denmark, including how the legislation should be changed and where the research for development within the $CO_2$ value chain should be done. A project concerning the Business Beacon of capture, utilization and storage of $CO_2$ is issued out for the Northern part of the country, Northern Jutland. In this area, the country's largest emitter of $CO_2$, Aalborg Portland, is located. Furthermore, a large number of biogas plants is located here, meaning that there are large quantities of $CO_2$ that can be retrieved from these point sources. Other than the point sources, the region also host harbours where $CO_2$ potentially can be shipped out or imported from or used as part of PtX when converted to e-fuels that can be used for ferries and fisheries.

A vital element to consider when planning for CCUS, is the configuration of which $CO_2$ sources that are qualified to be incorporated in a $CO_2$ infrastructure depending on their capacity of emitting $CO_2$ and their distance to the $CO_2$ sink. Other elements that are important to consider are, what the demand for $CO_2$ is, the type of $CO_2$ source, time frame, and mode of transportation.

# Research Question 5

A complete CCUS infrastructure consists of $CO_2$ sources, sinks and transportation of $CO_2$ in between these. To investigate how these elements should be planned for, several aspects should be included. As described in chapter 4, the size and type of $CO_2$ source matter to the capture of $CO_2$ and the technical and economic feasibility of transporting this via pipeline, truck, or ship. Furthermore, the capacity of the $CO_2$ transportation should be established to match the demand of eg. storages. These are elements that should be considered when investigating $CO_2$ infrastructure. Additionally, the CCUS infrastructure should be incorporated in a planning perspective, to ensure a holistic solution that is in line with the rest of the Danish energy system. The geographical scope of the infrastructure that is investigated in this report is Northern Jutland, based on the high $CO_2$ availability. On this background, the research question of this report is stated below.

## 5.1 Formulation of Research Question

*How can a CCUS infrastructure in Northern Jutland be planned for, based on planning prospects, $CO_2$ availability and spatial & economic feasibility?*

To elaborate on the research question, the following sub questions have been composed to aid in answering the research question and guide the analyses.

### 5.1.1 Sub Questions

1. How can CCUS infrastructure spatially and technically be arranged?
2. What is the spatial and economic feasibility of CCUS infrastructure?
3. How should the future CCUS infrastructure be implemented?

## 5.2 Delimitation

In this report, CCUS infrastructure covers the chain of handling $CO_2$ starting with the different points sources and which kinds of sources that can be included in a larger network for transport and utilization of $CO_2$. This also includes carbon capture facilities attached to the point sources. The next step is transport of $CO_2$ by either pipe, truck or ship, and what is the ideal mode of transport depends on a range of factors that the analyses investigate. The end point or sinks of the $CO_2$ is defined by different plans which include intermediate or long term storage. The CCUS infrastructure is investigated through the configuration of scenarios, that explores different arrangements of CCUS infrastructure.

The aim of this report is to assess a potential CCUS infrastructure in Northern Jutland. Some subjects that could have an influence on this are excluded from the scope of this report and not examined further.
There is a general discussion of which types of infrastructures and pipelines are needed to support the future energy system where e.g. hydrogen is a vital component, and where the current natural gas network is facing decommission [Evida, 2022]. This means that biogas and hydrogen are deemed to play a more prominent role in terms of transport in e.g. existing pipelines [The Danish Ministry of Climate, Energy and Utilities, 2021a]. The synergies that a potential $CO_2$-, hydrogen- and biogas infrastructure can have is further disputed by Evida, that is one of the actors involved in the planning of these [Kristensen, 2023]. However, the focus of this report is specifically on the role $CO_2$ will play and the configuration of the infrastructure. Therefore, the potential routes of the hydrogen and biogas network will not be included.
Another aspect to consider for the utilization of the $CO_2$ is the electrolysis needed for hydrogen and the upgrading and refining to e-fuels. The planned electrolysis and upgrading plants are included as sinks in terms of where the $CO_2$ is transported to, and is included as a type of storage with a certain capacity that is defined by technical and economic considerations in this report. This further means that alternatives to the location of these plants are not investigated. Furthermore, the processes that take place in PtX plants are not considered in terms of any costs or similar in the analyses in this report. Moreover, the internal project timeline of these projects and any potential ongoing upscaling of sizes and capacities is not considered, since the whole infrastructure at one point will have to handle the total planned amount of $CO_2$.
The analyses of $CO_2$ availability in Northern Jutland only takes point of departure in point sources where a carbon capture facility can be connected to either existing or future plants. This means that direct-air-capture and the amount of $CO_2$ to expect from this process is not considered.

## 5.3 Research Design

The figure below depicts the structure of the report and how this relates to the scope and the research question. The research design is divided into three pillars, representing the research questions, the chronological order of chapters of the analysis, and the theories and methods that are utilized to answer the research questions. Choice awareness and the technology definition makes out the general theoretical background of the report and aids in answering the first and third sub question. The sub questions are answered in the analysis of the report, that consists of three separate chapters. Various methods are applied and utilized to support various parts of the sub questions.

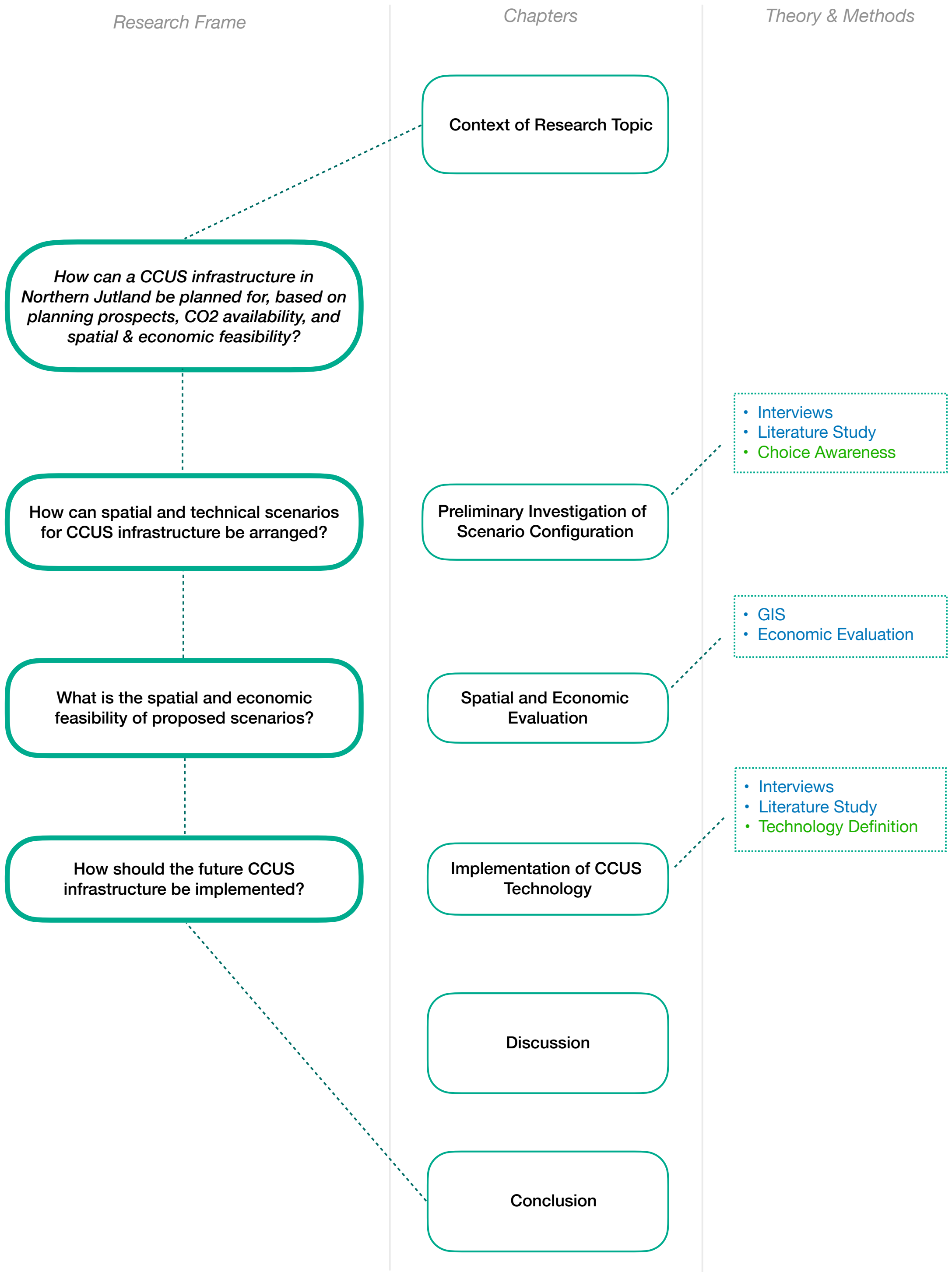


**Figure 5.1.** Illustration of research design.

# Analytical Framework 6

This chapter introduces the theories and methods applied in this report and thus constitutes the analytical framework. The analytical framework sets the environment for what is included in the analyses, outlines the analyses, and sets direction for how the research question is answered.

## 6.1 Theories

In this section, the theory of Choice Awareness and the concept of the technology definition is utilized to determine how the introduction of a CCUS infrastructure is a radical technological change, and how this change can be implemented in a Danish context. The theory is used to consider which planning elements that are essential when planning for a radical technological change such as CCUS infrastructure.

### 6.1.1 Technology Definition

To understand the level of change a CCUS infrastructure will impose on its surroundings the five components of the technology definition by Hvelplund and Djørup [2017] are applied: Technique, Knowledge, Organization, Products and Profit. This definition is used by Lund [2014a] to describe radical technological change in the energy system. This understanding of technology change impacts the analyses in this report by adding different dimensions relevant for investigation.
In order for the changes initiated by the technology (CCUS) to be implemented, a significant change in either or several of the components must happen. An example for the CCUS infrastructure is the Technique. The carbon capture unit itself is a new technique, and in a Danish context the $CO_2$ transport, storage and utilization is also new and have not been tested before. As mentioned in the delimitation in section 5.2, the technique involved in the utilization is not examined further. The change in Technique introduces changes in the other components as well. The changes in Technique requires new Knowledge on the matter to be formed by testing and ramping up capacities. On the Organizational level there is the question of who is to decide on the CCUS infrastructure, which sets new requirements on how to organize the implementation ie. by making sure that legislation is supportive of CCUS infrastructure. The 'Organization' aspect relates to the planning and implementation of CCUS which means that a societal aspect is investigated to fully understand how the radical technological change that a CCUS infrastructure is, should be planned for.
In terms of the Products component, another change is observed. The final CCUS infrastructure can be perceived as the product as this consists of all the technique elements,

combined. This adds another dimension that underlines the change that the technology will require to be implemented in the energy system. The Profit streams are also added to the technology definition. This aspect is highly connected to Organization and is relevant to consider when investigating who invests, constructs and owns the CCUS infrastructure and the different elements within. Understanding the nature of the Profit and streams helps evaluate who to involve in the planning and interpret underlining interests of the companies involved.
Figure 6.1 depicts how the five components influence each other in order to create a radical technological change.

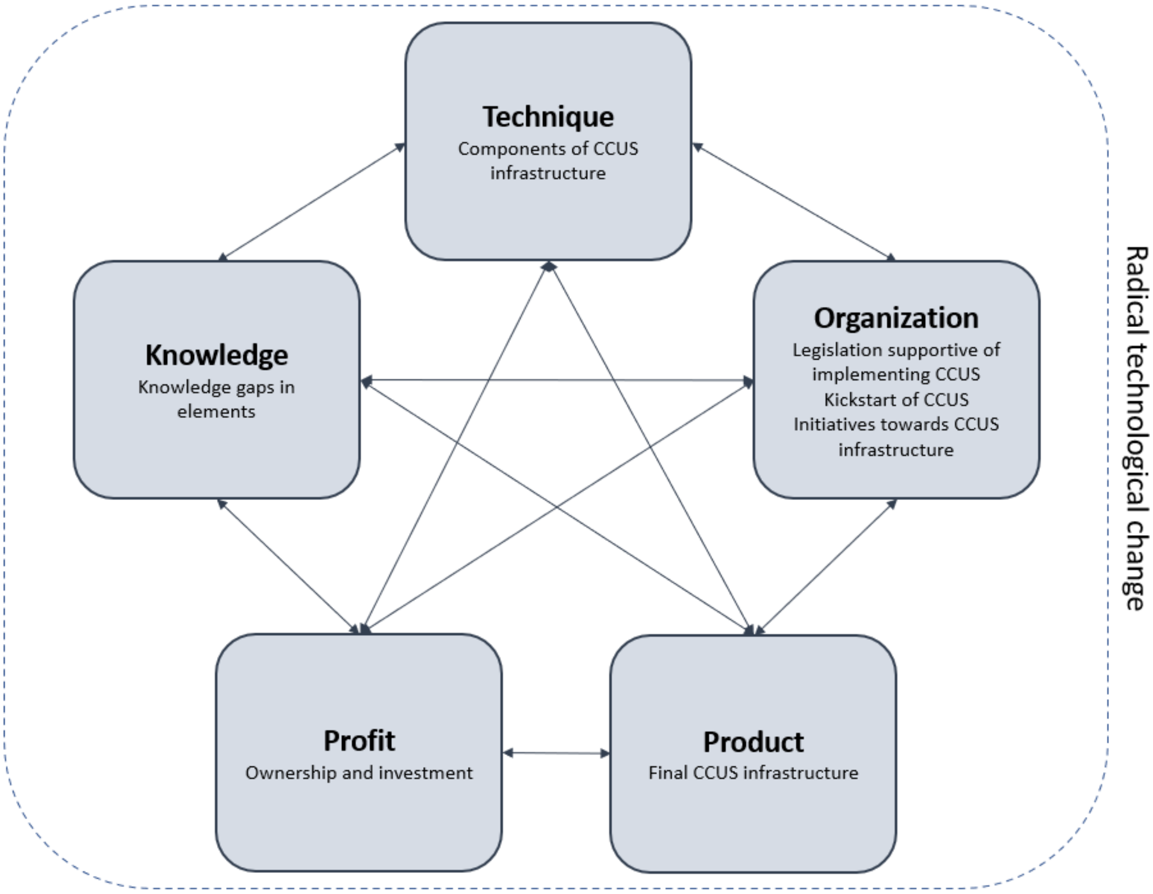


**Figure 6.1.** The radical technological change of the technology definition of CCUS infrastructure.

Because the change in technique initiates a change in all the technology aspects, CCUS infrastructure is perceived as a radical technological change, and these aspects are utilized in the analyses of this report in order to ensure a holistic perspective on the technology implementation.

In order to understand the subject of implementation of a technology, it must be defined what "implementation" includes. Based on the holistic view of the technology definition, the following definition is created to include all aspects of implementation.

This gives an understanding of what implementation entails when it is mentioned in this report:

*Implementation is defined as a process in which planning and execution of a subject or technology takes place. This entails initial analyses and examinations to the initiation of concrete plans and finally when the technology is constructed and in operation.*

### 6.1.2 How Radical Technological Changes are Implemented

Choice Awareness theory is concerned with how radical technological changes can be implemented, and how to create a true choice of technology options [Lund, 2014a].

The choice awareness theory was inspired by e.g. the 1990's where the transition to renewable energy was on the rise, and where the choice often stood between fossil fuel technologies, which was the known technology incorporated in the organizational setup, or the renewable technologies that were unknown to a greater extent than the fossil. In 2023, a large part of the organizational setup has been changed to accommodate renewable energy solutions, both through regulation, politics and in the norms of society. A lot of research is done to predict how changes in society and technology will affect the emission of $CO_2$, and based on these, choices of technologies are decided in political strategies and goals. Denmark has included a strategy to incorporate CCUS in its energy system, and this is backed up by research by eg. IPCC [2022]. It could be argued, that this is a representation of "no choice" - that either CCUS is implemented, or the $CO_2$ emissions will continue, and the climate goals will not be met. In the text by Lund [2014a], the definition of sustainable energy is also an important factor when creating choices. CCS and nuclear are in the text exemplified as elements that can be promoted as sustainable, in order to convince renewable energy "supporters" to support coal and nuclear using technologies. Therefore, it is important that when CCUS is examined in this report, the sustainability and time perspective is imposed to ensure that this technology does not create a carbon lock-in – ie. creating a dependency of fossil energy. Plants that have the prospect of transitioning to renewable fuels are excluded. Examples of this is the combined heat and power plant Nordjyllandsværket that will be decommissioned in 2028 and uses coal as fuel [Aalborg Utilities, 2021].

In this report, it is assumed that the choice of CCUS in Denmark has been made, and that it is necessary to meet the climate goals by 2030 and 2045, since most analyses of the future energy system includes carbon capture as a technology that is included on equal terms as other renewable energy technologies. This diminishes the objective of discussing whether the technology sets up a "no choice" situation. The specific design of how it is constructed and implemented is however still to be decided. This report dives into how a CCUS infrastructure in Northern Jutland could be outlined and is based on the potential of both sources and sinks and the transport of these.

As emphasized in section 4.4, a CCUS infrastructure consists of several techniques and can be organized in several different ways. Within a CCUS infrastructure, different solutions could be chosen, creating a choice within the technology of CCUS, that also can affect and is affected by policies and regulatory set-up in the country and the EU. To underline the importance of having options to choose from and thereby creating a choice, different scenarios for CCUS infrastructure is presented in the analyses of this report.

The set-up of scenarios, or technical alternatives, is a part of the Choice Awareness methodology, where it is emphasized, that alternatives should be seen in and related to the existing organizational and institutional context, since this can change the feasibility of an alternative, even though it is the best technical alternative. Furthermore, it is emphasized that the investigations of alternatives should be made comparable [Lund, 2014b]. This consideration is included in the way the economic evaluation of the scenarios is set up, which is described in section 6.2.

## 6.2 Methods

In this section, the methods that are used in this report's analyses to answer the research question are described. The use of both qualitative methods, such as interviews, combined with quantitative methods, such as GIS analysis and economic evaluation contribute to a comprehensive analysis of a CCUS infrastructure in Northern Jutland.

### 6.2.1 Interviews

For further insight to the CCUS infrastructure, and what elements to consider when planning for this and other relevant factors, interviews are conducted as a method of research.

**Selection of relevant actors to interview**
For the purpose of expanding the knowledge needed for analyzing the introduction of a CCUS infrastructure in Northern Jutland, actors that work within the value chain are to be included in the report. In order to determine which actors that are relevant to include, this section involves an overview of relevant actors that can contribute to the analyses of this report. The value chain of a CCUS infrastructure is set up in figure 6.2 to help determine which actors that are relevant to include in the report's analyses.

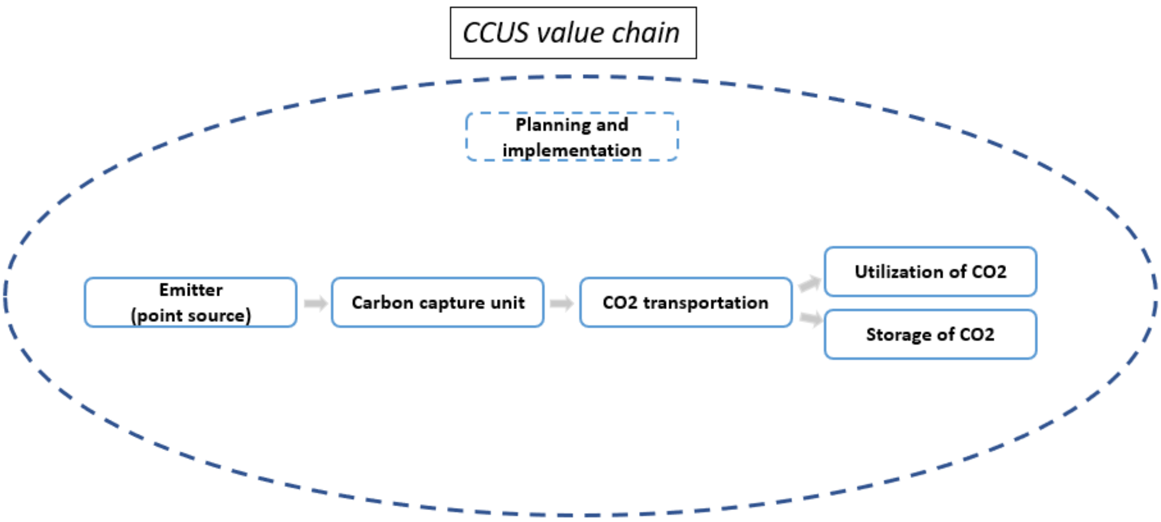


**Figure 6.2.** The value chain of CCUS infrastructure.

The value chain is divided into different categories, in which different actors can have their own opinions, goals and knowledge about how a CCUS infrastructure should be composed.

The actors that relate to the CCUS development are initially found through brainstorming and a review of the current research and papers that are done on CCUS infrastructure in Denmark. The key actors that have produced articles and research on the topic, or that are included in these, are depicted on figure 6.3.
The actors are divided by their willingness to influence the development and planning of a CCUS infrastructure and to which degree they can influence a such planning. Furthermore, the actors are split in two groups on whether their influence consists of a direct or indirect type.

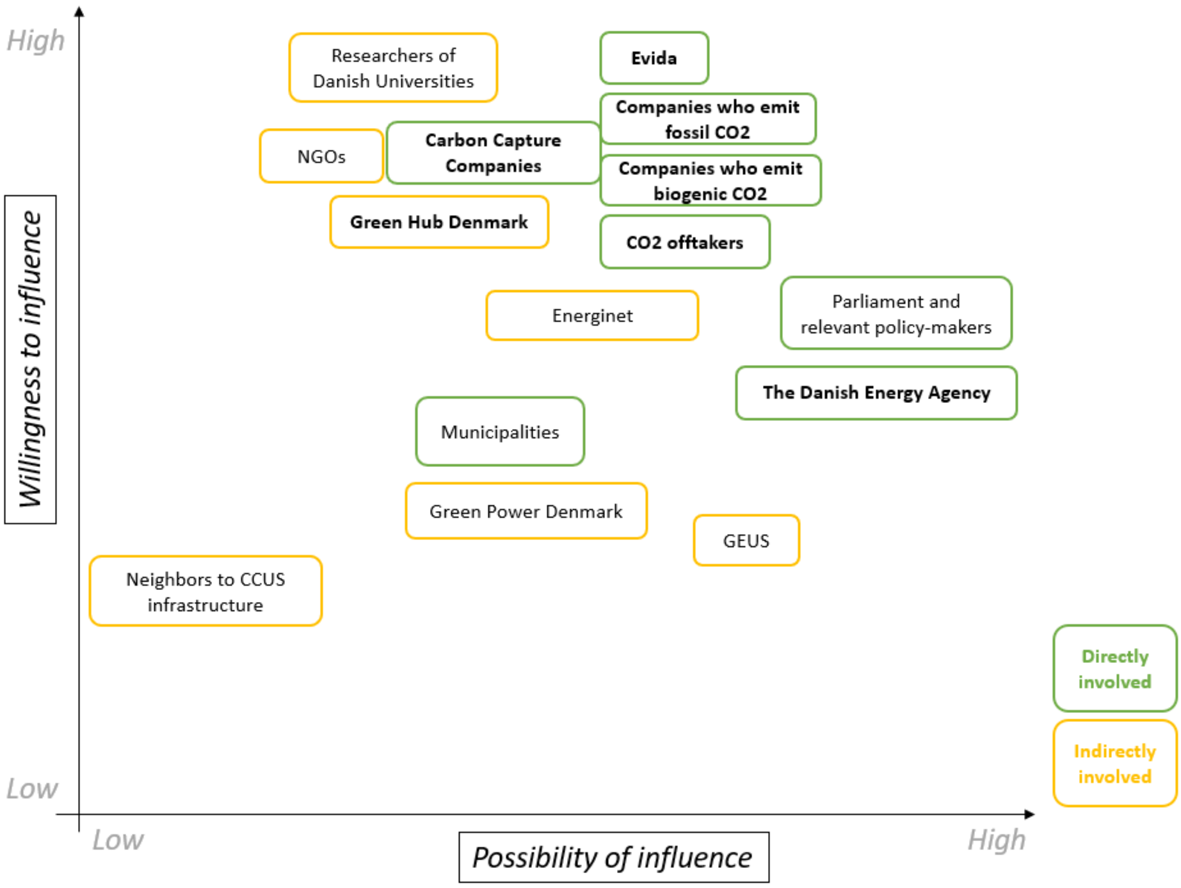


**Figure 6.3.** Actors involved either directly or indirectly with CCUS infrastructure in Northern Jutland and categorized according to their willingness to influence and possibility of influence on the decision-making of the infrastructure. The interviewees of this report are highlighted with bold font.

The figure indicates potential actors for interviews of their role in the planning of CCUS infrastructure.

The actors that are selected for interviews in connection with this report are those who are relevant in the development of the potential CCUS infrastructure in Northern Jutland. Since the development is still on an early stage, some actors are thereby more relevant than others, and others are more relevant in a later stage when there are more concrete development plans and detailed configuration of the CCUS infrastructure.

The specific actors that are interviewed and the set-up of the interviews, are described below.

- **The Danish Energy Agency:** The agency is an important part of setting the tone, deciding and creating regulation that have a high influence on the development of CCUS infrastructure [The Danish Energy Agency, n.d.b]. Therefore, it is relevant to interview a representative from the Danish Energy Agency.
An interview with Theis Dekker Gjedsted, who is a special advisor at the Danish Energy Agency, was conducted on the 26th of April 2023 on Microsoft Teams. Information from this interview is referenced as Gjedsted [2023].
- **Evida:** This state-owned company have besides the distribution of natural gas also been given the opportunity of investing in and maintaining a $CO_2$ infrastructure by pipes [Evida, 2023]. This role makes them highly relevant to investigate in terms of their responsibility and attitude towards a such infrastructure in Northern Jutland.
An interview was conducted on the 26th of April 2023 with Janus Rathke, who is a business developer at Evida, on Microsoft Teams. Information from this interview is referenced as Rathke [2023].
- **Biogas Denmark:** The industry association of biogas plants in Denmark is relevant to interview since they can provide the point of view from an important contributor of biogenic $CO_2$ to the CCUS infrastructure [Biogas Denmark, n.d.].
An interview was conducted on the 27th of April 2023 with Mads Wagner Dahl, who is a technical analyst at Biogas Denmark, on Microsoft Teams. Information from this interview is referenced as Dahl [2023].
- **Danish Gas Technical Center:** The entity owned by Evida have contributed to the knowledge base regarding road maps of how CCUS can be implemented in Denmark and what aspects are relevant to highlight in this regard [The Danish Gas Technology Centre, n.d.].
An interview was conducted on the 1st of May 2023 with Kate Harboe, who is a project manager and chemical engineer at Danish Gas Technical Center, on Microsoft Teams. Information from this interview is referenced as Harboe [2023].
- **Green Hub Denmark:** The partially public and private research hub is an organization who connects companies, consumers, researchers and authorities to produce green solutions and contribute to growth. They have been coordinating the work for the Northern Jutland Cluster on CCUS [Green Hub Denmark, 2022]. Therefore they are a highly relevant actor with opinions and knowledge base regarding what constitutes a CCUS infrastructure specifically in Northern Jutland and which barriers and advantages there might be.
An interview were conducted on the 4th of May 2023 with Mette Høj Ravnborg, who is a project manager at Green Hub Denmark, on Microsoft Teams. Information from this interview is referenced as Ravnborg [2023].
- **Aalborg Portland:** As the largest emitter of $CO_2$ in Denmark and a company in a hard-to-abate sector Aalborg Portland are significant to interview in terms of their opinion on aspects such as ownership, barriers and incentives to initiate a CCUS infrastructure [Aalborg Portland, 2022].
An interview was conducted on the 10th of May 2023 with Jesper Sand Damtoft, who is group sustainability and R&D director at Cementir Group, on Microsoft Teams. Information from this interview is referenced as Damtoft [2023].

- **European Energy:** As a company developing Danish PtX projects utilizing $CO_2$ to produce e-fuels, European Energy is a representative for the consumers of $CO_2$ [European Energy, 2023]. This is an important aspect since it is relevant to investigate their attitude towards initiatives and ownership of a CCUS infrastructure.
  An interview was conducted on the 12th of May 2023 with Lotte Lindeloff, who is director of PtX project management at European Energy, on Microsoft Teams. Information from this interview is referenced as Lindeloff [2023].
- **Ammongas:** Develops and installs solutions for pollution control systems and e.g. carbon capture plants and is thus a company participating in the CCUS value chain [Ammongas, n.d.].
  An interview was conducted on the 12th of May 2023 with Tim Nærvig, who is head of carbon capture at Ammongas, on Microsoft Teams. Information from this interview is referenced as Nærvig [2023].

The interviews that are held in this report, are all carried out in a semi-structured way, which means that for each interview, there is a prepared written interview guide, giving an overview of which topics and overall questions that are in the interview. For all interviews the same outline of the interview guide was used, with few exceptions that only were relevant for the interviewee in question. At the same time, the interviewer and the interviewee have the possibility to advert from the questions and topics of other elements that are relevant for the overall purpose of the interview. Some of the utilized statements from the interviews are updated based on feedback from the interviewees.
It can be observed that the all aspects of the value chain are covered with these interviewees, which in turn increases the validity of the results in which these actors contribute to.

Interviewing different sources for the same topic of investigation ensures a higher degree of reliability that further highlights the validity of the results that is provided by the basis of the interviews. However, it is important to acknowledge that some subjects might have a degree of personal opinions, but this is to a wide extent mitigated by following the interview guide. The interview guide is located in Appendix A.11.
The processing of the data from the interviews are based upon the five components of the technology definition by Hvelplund and Djørup [2017] and Lund [2014a]. This means that the answers from the interviewees are divided into the category of either; technique, product, profit, organization and knowledge, in order to investigate how the CCUS implementation is impacted by each of these categories, and further what aspects are most pertinent. This results of the processing of the data is located in Appendix A.12.

### 6.2.2 Spatial Analysis Methodology

Understanding the spatial conditions of CCUS infrastructure is aided by the use of Geographic Information System (GIS). GIS can connect and map a wide range of data, and this ability to showcase data is vital when exploring the local context of a new type of infrastructure that is to be implemented [Esri, 2023b]. The applied software in this report is ArcGIS Pro that is a desktop app that can visualize, process and analyze geospatial data [Esri, 2023a].

GIS is utilized to process quantitative spatial data that will be conveyed to form and assess different scenarios for a CCUS infrastructure. These scenarios are based upon the capacity of $CO_2$ emission given by the point sources.

**Network Analysis**
In this analysis, network analysis in GIS is used as a way to analyze the feasibility and best solution of specific scenarios for CCUS infrastructure. In general, a network analysis is centered around networks and the problems that can arise within these. This could be finding the quickest route between two points and getting directions for this, or it could be figuring out how much of a community that can reach a certain point within 5 km [de Smith et al., 2018].

In ArcGIS, there are different possibilities for using a network analysis tool, common for all of them is, that an existing network layer – in this case, the road network, is required to perform the analysis [Esri, 2021]. The tool can be used to determine the fastest or shortest route from a point to a destination, which can be used when assessing the feasibility of truck transportation of $CO_2$.
The specific tool that is used in ArcGIS Pro is the Network Path Planner that can aid in proposing a network route [Esri, n.d.].
This is a network analyst tool, that can be used to find the shortest route in a network, while connecting all point sources to sinks, thus creating a combined network [Esri, n.d.].
The results from this analysis are used to apply economic inputs and thus perform an economic evaluation of the different scenarios.
The methodology for the input for the use of the path planner to create a $CO_2$ network in Northern Jutland is described below:

1. The road network of Northern Jutland is used as the network data set.
2. The sinks appointed for the CCUS infrastructure is added as Network Locations. This means they are the point features from where the routes for the network starts.
3. The chosen point sources are set as Target Locations, which is the point features that marks the end of the routes calculated by the path planner. This distinction between Network Locations and Target Locations ensures that the optimal routes are found.
4. All point features have been forced to take part in the same network, by the addition of a field 'NetworkName' with identical input in the attribute. This is to ensure a continuous network between all point sources and sinks.
5. No route modifiers or cost adders have been added to the path planner tool. This causes the network to not be restricted, and thereby find the optimal routes.
6. The input to the path planner is then utilized to retrieve the network.

The spatial analysis together with the economic analysis provides a basis for estimating different scenarios for CCUS infrastructure and evaluate what options seems most feasible in the future.

**Data collection**

The fundamental input data in the Network Path Planner tool are the network dataset, point sources, and sinks of Northern Jutland which are used to calculate the routes and combined network for the scenarios. Since a GIS analysis for the research project CO2Vision using the road network and $CO_2$ point sources in Northern Jutland, this data is also used as input for the network analysis in this report. The input data for sinks are made by creating a point layer containing points for expected PtX plants with a $CO_2$ demand, as well as points for possible long-term storages, both onshore and nearshore.

### 6.2.3 Scenario Setup

The CCUS infrastructure is in this report investigated through a set-up of scenarios. As described in section 6.1, scenarios or alternatives should be comparable. Therefore, the scenarios in this report are each compared by their technical content and economic input and calculations. The technical input that the scenarios consist of, are as follows:

- Amount of captured $CO_2$ in each scenario.
- Amount of $CO_2$ transported to sinks.
- Length of network routes.
- Map showing location of point sources, sinks and network.

Based on The Danish Energy Agency [2021d], the economic input that are included for each scenario are as follows:

- Investment cost of each component in the technology
- Operation and maintenance cost
- Scrap value cost
- Price of $CO_2$ emission allowance
- Cost of $CO_2$ tax
- Discount rate
- Net tax factor
- Distortion of taxes and levies

These input are further described in the description of data collection of the socio-economic evaluation. The setup of the scenarios ensure that the subsequent spatial and economic comparison is made on an equal basis.

### 6.2.4 Socio-Economic Evaluation

To evaluate the profitability and economic feasibility of a future CCUS infrastructure project, the net present value (NPV) of the scenarios of the potential infrastructure is calculated. When the resulting NPV value is positive, it means that the investment is paid back within the timeline of the project, and is therefore socio-economically feasible. The point of departure for the calculation of the NPV is a socio economic standpoint, where all investments are joined even though the investments might not be made by one actor. Large-scale energy related projects are often evaluated in this way [The Danish Energy Agency, 2021d]. This means that the scenarios are evaluated equally and systematically and with the same input and the results of such an analysis shows the total consequences such a project will have on society. Another part of the socio-economic evaluation is the inclusion of factors such as emissions that are part of projects [The Danish Energy Agency, 2021d].
The NPV can be expressed as the sum of the current value of future cash flows [Serup,

2010]. The time dimension is the valuable aspect of the NPV as the *discount rate* adds the value of money in the future [Fernando, 2022]. This is relevant for CCUS infrastructure as it requires a significant investment, that will not be paid back immediately, and the future value of this investment can be decisive for the planning and implementation of a CCUS infrastructure.
The NPV formula as expressed by Serup [2010] can be seen below:

$$Net\ Present\ Value = \sum_{t=0}^{n} NP_t \cdot (1 + Discount\,rate)^{-t} \tag{6.1}$$

Each of the factors in the formula can be described as:

- $NP_t$ the net payment at time $t$
- The duration of the investment is expressed by $n$
- The *discount rate* factors in the time aspect of the investment by converting this and is also the interest rate. The rate can furthermore be described as the outcome of a potential alternative investment [Fernando, 2022].

The NPV calculation of the scenarios are conducted in Excel which is a software used for data analysis [University of Washington, 2021].
Included in the NPV as the $\mathrm{NP}_t$ is the annual cost. This approach is useful when calculating and comparing costs when there are different timelines involved in projects [Kenton, 2020]. This is particularly useful for CCUS infrastructure, where the lifetime of a truck compared to a pipeline can have an impact on the investment made and the annual cost. The annual cost calculation also includes a discount rate that is the necessary return to make the investment of a project worthwhile [Kenton, 2020]. The formula used to express this:

$$Annual\ Cost = \frac{Cost\ + Discount\,rate}{1 - (1 + Discount\,rate)^{-t}} \tag{6.2}$$

where $t$ is time, and *costs* is the summation of all related costs to the infrastructure.
Utilizing both methods helps evaluating the socio-economic impact of the CCUS infrastructure and thus heightens the validity of the results as these can be compared to find the scenarios that are most attractive.

An additional method to comparing the scenarios among themselves is to investigate the yearly costs of each scenario, and comparing this to how much $CO_2$ that is captured, transported, or stored or utilized from each technology.

**Data collection**

The input for the NPV calculation is based on the technical items that are part of the CCUS infrastructure, which all have a cost added as well as the interest rate. To fully understand the size of the investment needed for the CCUS infrastructure, a breakdown of the costs is needed which can be found in appendix A.
The economic input that is needed for the report's economic analysis is regarding the investment and O&M costs for the technologies that can be used in the CCUS

infrastructure, which is the capture facility, the transport modes, intermediate storage and the long-term storage. The economic data for each technology is derived from "Technology data - carbon capture, transport and storage" by The Danish Energy Agency [2021e]. The discount rate for the analysis is based on the discount rate defined by The Danish Ministry of Finance [2021] for projects within 35 years of lifetime which is then 3.5%. 30 years of calculation for the scenarios is chosen due to this being the approximate average lifetime of the technologies in the CCUS infrastructure. The net tax factor describes the average size of indirect taxes, levies and subsidies which is added to the private consumption and is defined by The Danish Energy Agency [2021d] as 28% and is then multiplied by all inputs, ie. the price of $CO_2$ emission allowances, $CO_2$ tax, and costs of investments and O&M to establish these in market prices. The distortion of taxes and levies is added a percentage of 10% also described by The Danish Energy Agency [2021d]. This factor describes the change and distortion of taxes and levies which is impacted by such projects as the CCUS infrastructure and this describes the impact of the redistribution of the taxes in a socio-economic sense.
An element of the socio-economic evaluation are relevant taxes and emission allowances. The $CO_2$ tax implemented in 2030 is 100.7 €/t $CO_2$ for all companies except companies with mineralogical processes such as Aalborg Portland where it is 16.8 €/t $CO_2$ [The Danish Ministry of Finance, 2022]. The price of $CO_2$ emission allowances is set at 99.1 €/t $CO_2$ in 2030 and relates to the allowances that can be sold, when emitters capture their $CO_2$ instead of emitting it to the atmosphere [The Danish Energy Agency, 2022]. The input of the economic assessment is included in Appendix A.

**Sensitivity Analysis**

In order to fully evaluate the outcome of the economic analysis and the results thereof, a sensitivity analysis is conducted. The analysis aids in understanding the uncertainty of the numerical output of the economic analysis [Saltelli, 2002]. The analysis helps understand which factors are the main risks for the investment in CCUS infrastructure, and thereby help in mitigating risks [Christopher Frey and Patil, 2002].
According to Saltelli [2002] the objective of the sensitivity analysis is to find the factor that has the greatest influence on the results. This influence is found by changing one input factor at a time, and thereby assess the relative change in the results.
In this report a graphical approach is chosen to visualize the sensitivity analysis, since this approach by the use of either graphs, charts or similar indicate the impact the variation in input has on the output [Christopher Frey and Patil, 2002]. A risk related to the method is that the correlation between input factors might not be captured, when these are linearly and independently changed [Christopher Frey and Patil, 2002]. However, the sensitivity analysis can provide vital insights to the factors that have an impact on the economic results. Relevant inputs are changed by e.g. +/- 20 % or using low and high prices, as suggested by The Danish Energy Agency [2021e]. The exact input to the sensitivity analysis is displayed in Appendix A.10.

# Preliminary Investigation of Scenario Configuration 7

This chapter introduces the elements that is a part of the future CCUS infrastructure in Northern Jutland that will be included in a spatial and economic evaluation. This includes an analysis of the relevant point sources to capture $CO_2$ from, which carbon capture technology to select, and which sinks are applicable for the future prospects of the infrastructure. The purpose of the chapter is to give a background of the elements that will constitute the scenarios for further investigation. The elements will be arranged in different ways in order to find how the elements of the CCUS infrastructure impacts each other and the total infrastructure.

## 7.1 Point Sources

The applicable $CO_2$ point sources for the CCUS infrastructure and the selections and delimitations of the process of analyzing these are presented in this section.
For the analysis of this report, only $CO_2$ sources of Northern Jutland are included. These are divided into groups depending on their origin; industry, biogas or expected biogas, waste incineration, heat and electricity. The largest $CO_2$ emitter in Denmark, Aalborg Portland is given their own category due to their large emissions. In total there are 1,040 point sources, where over half of these are industrial point sources. The total amount of point sources are filtered in regards to what is found to be feasible scenarios to include in a CCUS infrastructure.

A general cut-off value for which $CO_2$ sources that are large enough to include in a CCUS infrastructure is not officially set and different analyses have different values for how large a $CO_2$ emission a point source should have to be included in an CCUS infrastructure. According to The Danish Energy Agency [2021e], post combustion capture plants can be used on point sources with as low as 1,000 t $CO_2$/year. Green Hub Denmark [2022] includes point sources that have a minimum of 5,000 t $CO_2$/year in their analysis which is described as a low threshold. However, they gather from a capture company, that their smallest capture plant should be able to recover at least 40,000 t/year to have a feasible business case.
Based on these statements, two versions of the data are made to represent a "lower" and "higher" threshold for which point sources to include. One version includes all sources that have a recovery potential over 1,000 t $CO_2$/year and one version where only point sources with a potential larger than 40,000 t $CO_2$/year are included. This is to investigate the feasibility of either threshold and the impact of this on the combined CCUS infrastructure. In both of these versions, the heat and electricity producing units are removed, with the

assumption that these will produce less and be electrified to a wide extent in the future [Lund et al., 2021]. Therefore, to minimize the risk of carbon lock-in and unnecessary investments they are excluded from further analysis. Furthermore, it will be considered which of the industrial point sources that are expected to be electrified in the future, and thus wont be included as a $CO_2$ source [The Danish Energy Agency, 2021b].
This means that generally, industries that have production processes with temperatures above 500 °C are included, whereas industries below this threshold or where it is expected that is is possible to transfer to other production methods are excluded from further analysis. The expected increase and expansion of biogas plants in Northern Jutland is also included in the two versions to ensure that the investigated infrastructure fits to the maximum $CO_2$ potential.
When these filters are added to the total amount of point sources, the $CO_2$ point sources are reduced to respectively 42 and 11 points. The point of departure for $CO_2$ emissions from these point sources are the current emissions and not what can be expected in the future in order to estimate the potential of a CCUS infrastructure in a near future.

Another version of the point source data includes the expected change of $CO_2$ potentials in 2045, based on "IDAs Climate Answer 2045" by Lund et al. [2021]. This scenario is based on all sources with more than 10,000 t $CO_2$/year, and also does not include the heat and electricity producing units, since they in the future will be operating less because of the increase of heat pumps and renewable electricity in this sector [Lund et al., 2021]. Furthermore, most industries except Aalborg Portland, Rockwool and Vindø Tegl are expected to be electrified by 2045, based on their potential to change technologies in their production, erasing their potential to export $CO_2$ [The Danish Energy Agency, 2021a]. However, the industries that are not electrified, will still reduce their emissions compared to 2030, since the industries can be partially electrified or change fuels to natural gas, which minimizes the emission [The Danish Energy Agency, 2021a]. The potentials for $CO_2$ from waste incineration are reduced as there in general will be a smaller production of waste and a higher amount of recycled waste [The Danish Government, 2020]. Lastly, the biogas production is increased as straw and more organic waste is moved to biogas production from waste incineration [Lund et al., 2021]. This scenario thus has a 2045 perspective, which is used to display the scenario's feasibility in the future, since the investment decisions for the infrastructure should fit both the current and future potential $CO_2$ transport demands.

In summation, the spatial analysis and economic evaluation of this report includes three versions of point sources:

1. Point sources $>$ 1,000 t $CO_2$/year
2. Point sources $>$ 40,000 t $CO_2$/year
3. Point sources based on IDAs Climate Answer 2045

On the map in figure 7.1, the point sources that are over 1,000 t $CO_2$/year are illustrated.

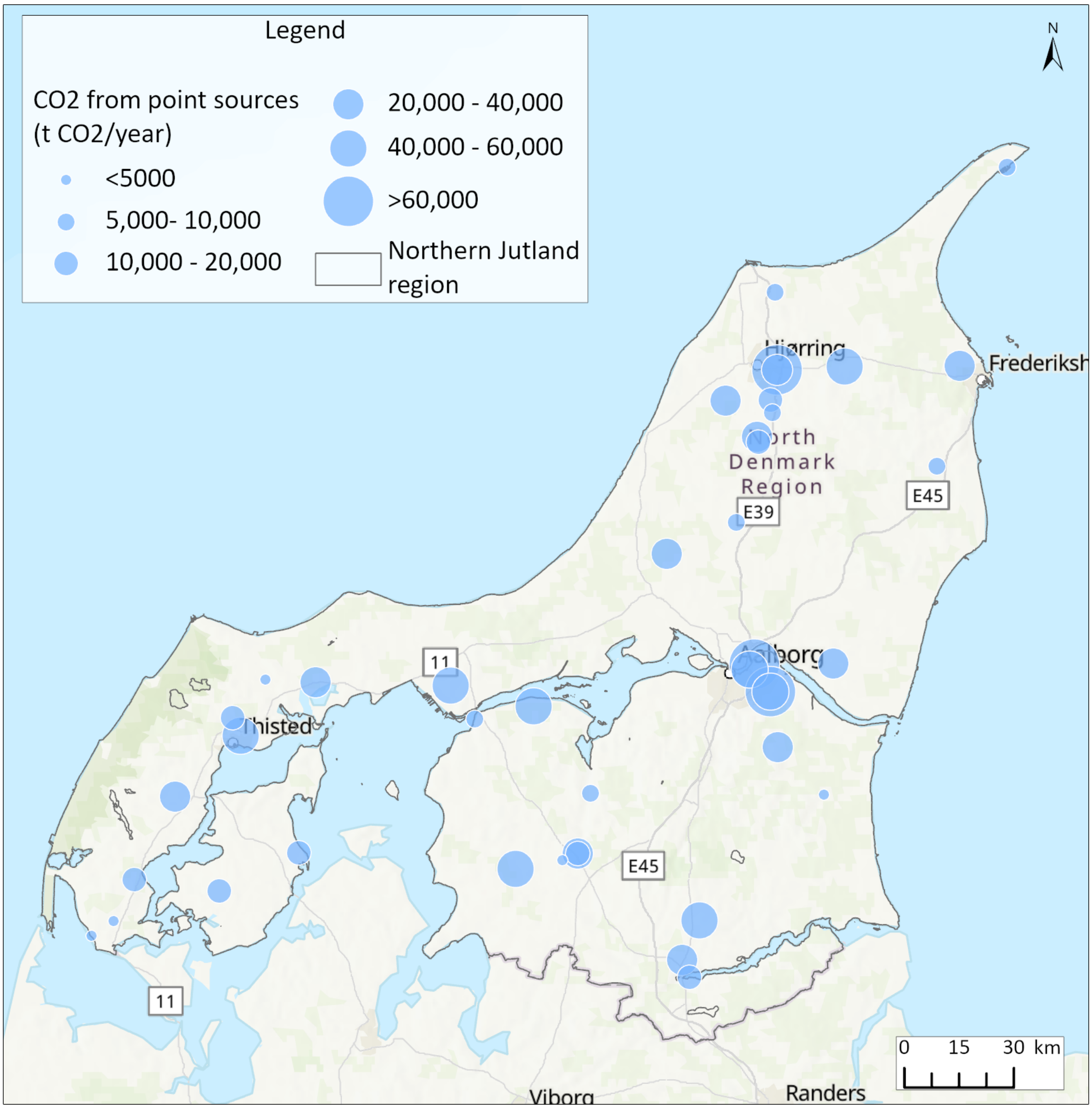


**Figure 7.1.** Location of $CO_2$ point sources > 1,000 t $CO_2$/year.

The total potential for recovery of $CO_2$ from the point sources in the different data versions used in this report's scenarios are shown in figure 7.2.

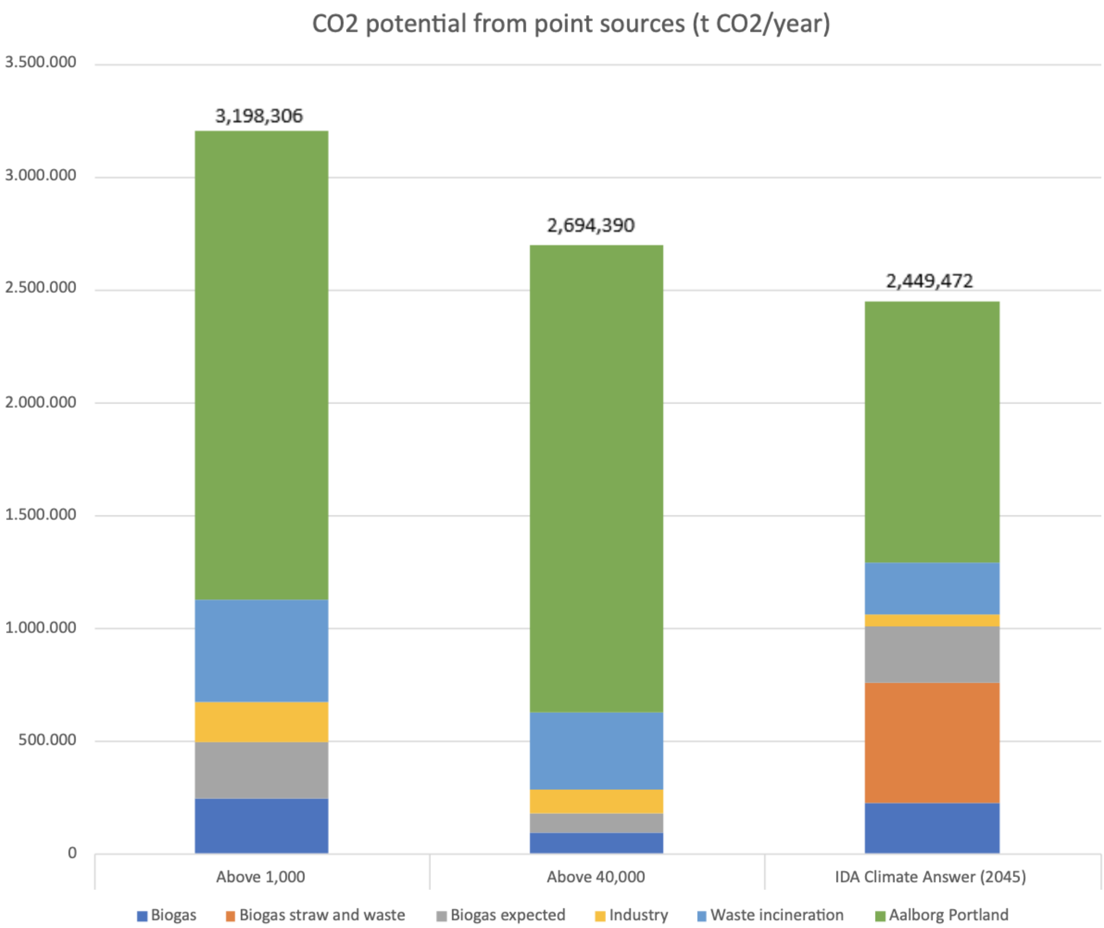


**Figure 7.2.** The potential for $CO_2$ recovery from each data version of point sources, divided in sectors.

### Fossil and biogenic $CO_2$

The captured $CO_2$ from point sources can be divided into fossil and biogenic shares of $CO_2$ for several point sources, such as waste incineration and industries.
Some of the industries that will not be electrified, currently emit fossil $CO_2$ because they use coal, petcoke or oil as a fuel. According to The Danish Energy Agency [2021c], these have the potential to redirect their production to using natural gas or biogas as a fuel. Since biogas is expected to replace natural gas in the future, and since $CO_2$ emission from combustion of biogas is 100 % biogenic, the $CO_2$ from these sources are also assumed to be 100 % biogenic.

## 7.2 Description and Choice of Carbon Capture Technology

To determine which type of carbon capture unit that is utilized for further analysis, this section includes a description of their advantages and disadvantages. The choice of technology is made based on the advantages of the technology, and the future perspective of it. Unless other is stated, the information of this section is derived from the The Danish Energy Agency [2021e] "Technology Data - carbon capture, transport and storage". This source is based on an aggregation of multiple other sources and takes a point of departure in a Danish context [The Danish Energy Agency, 2021e] – therefore, this is considered state of the art within the technologies used for CCUS infrastructure.

**Amine Post Combustion Carbon Capture**
This technology has the capacity to capture up to 90 % of $CO_2$ from flue gasses by using an amine solvent to "scrub" the $CO_2$. The amine post combustion solution can be retrofitted to most existing plants, such as heat and power plants, as well as industrial utility boilers and cement kilns. Some of the main advantages from the amine post combustion technology is that it has been utilized over several decades and therefore has a higher technological readiness level. Furthermore, the technology can easily be retrofitted to an existing, operating plant and can be used for several different fuels. Some disadvantages are that there are high requirements to the purity of the flue gas, meaning that the flue gas often must be pre-treated. The technology has a high energy use, especially in terms of thermal energy use for the amine solution. Environmentally speaking, emission of the amine solution to the air can have harmful effects on the environment – this is a focus in the development of the technology, where emissions have been lowered. The purity of $CO_2$ from this technology is around 99.5 % or higher.

**Oxy-fuel Combustion Carbon Capture**
Oxy-fuel combustion uses a higher amount of pure oxygen in the combustion process, by removing nitrogen before combustion, resulting in a flue gas that mainly consists of $CO_2$ and $H_2O$. It could be possible to recover 70-75 % of the $CO_2$ from a plant running full load with a retrofitted boiler. The technology is more suitable for a plant with a base load production profile, than a fluctuating production. A significant difference in this technology compared to the post combustion carbon capture, is that there is a need for an $O_2$ source, that can be delivered from an air separation unit (ASU), or from electrolysis – the latter can however have difficulties in terms of variation in operating hours. Another difference is that the $CO_2$ output is not as pure as when using the amine solution, which means that further post treatment of the $CO_2$ is needed – the purity from the oxy-fuel combustion technology can be between 70 and 90 %. This is a new technology, and no commercial scale plants have been built yet, but several demonstration or research plants have. The advantages of this technology is that an existing boiler can be changed to oxy-fuel combustion. In regards to the financial aspect, the technology can result in a lower CAPEX compared to post combustion capture, but this cost reduction might be smaller or leveled out, depending on the $O_2$ source and the cost of this – ie. if the $O_2$ comes from an electrolysis plant as an excess product, or if there is a further investment in an ASU. The technology is more effective in a cement plant, but it does however require a substantial retrofitting, where the cement plant can not be in operation. In this technology, no chemicals are being used.

Amine post combustion carbon capture is the technology that is already used in commercial scale, and therefore have the least uncertainties regarding costs and design. Oxy-fuel can have a lower CAPEX, but is especially suited for base-load technologies. Considering the lower technological readiness level and the flexibility that amine post combustion has in terms of being able to be retrofitted to most production plants, oxy-fuel is not used in the analysis of scenarios. Therefore, amine post combustion is used for all point sources where carbon capture is added.

After the carbon capture, the $CO_2$ must be transported either through pipelines, ship or

truck transport to a permanent geological storage or used in production of e-fuels. The general term for these are sinks.
The quantity of $CO_2$ and the length of transportation determines which mode of transport is the most feasible. Usually truck transport is used for shorter distances and smaller quantities – it is difficult to determine exactly where the distinction between trucks or pipelines should be made, and it can depend on specifications of each transportation route.

## 7.3 Potential Sinks For CO2 Transportation

Overall there are three types of sinks; storage sites, export sites (intermediate storage) and sites for utilization of $CO_2$. This section features an overview of the relevant sinks and their potential in connection with the CCUS infrastructure.

### Storage Sites

This type of sink can be defined as geological storage, and the objective of this sink is to permanently keep the $CO_2$ in this type of storage [COWI, 2021]. In this report, these storage sites are regarded as the end of the cycle for the $CO_2$, and it will not be possible to remove any $CO_2$ later on from these sites. The captured $CO_2$ is to be compressed, transported and pumped into the underground in a porous and permeable type of soil and depth to encapsulate the $CO_2$ [GEUS, n.d.; Rambøll, 2022]. According to GEUS, there is one onshore geological storage site for $CO_2$, the Gassum site, and four nearshore storage sites (Inez, Lisa, Jammerbugt and Hanstholm) which all are close to Northern Jutland and fit to long-term $CO_2$ storage [Green Hub Denmark, 2022].
All five areas are deemed to live up to the criteria for a geological storage, though the exact capacity of each reservoir is unknown [GEUS, 2021]. The Gassum formation near Hobro is expected to have a capacity of 584 Mt $CO_2$, which indicates that there is enough capacity for many years of storage [Hjelm et al., 2020].
These five storage sites are pointed out by Green Hub Denmark [2022], Rambøll [2022] and Thisted Municipality [2020] as relevant in the context of Northern Jutland and the potential as storage sites is thereby confirmed. Offshore sites are not taken into consideration as it is deemed that the appointed sites have enough capacity to handle the expected amount of $CO_2$ from Northern Jutland intended for long-term storage, and generally the capacity in these geological reservoirs are assumed not to be a constraining factor [GEUS, 2021]. Furthermore, these sites are already being explored and studied for $CO_2$ storage [Hjelm et al., 2020].

### Sites for Export of CO2

The ports in Northern Jutland can prove to have a valuable location in terms of export and import of $CO_2$ or e-fuels produced on the basis of $CO_2$ and green hydrogen [Green Hub Denmark, 2022]. The intermediate storage at ports present a buffer that can ensure continuous supply or transport of $CO_2$ to storage sites offshore and thus guarantee a security for any type of breakdown in the CCUS value chain [Axcelfuture, 2022]. The sizes of these type of storages depend on a weighing of economic and technical considerations. According to The Danish Energy Agency [2021e] this type of storage have a capacity of

approximately 3,000 ton or 14,000 ton.
The Marco Polo project highlights *Hanstholm* and *Frederikshavn* ports as potential sites for methanol production and export, which is why these are pointed out as potential sinks [Energy Cluster Denmark, 2022].
According to Green Hub Denmark [2022] other relevant ports for the potential CCUS infrastructure are *Port of Aalborg* due to the proximity of large $CO_2$ point sources and PtX projects, and *Hirtshals* port due to the project 'GreenPort Scandinavia' where the port is appointed as the nodal point for disembarkation for storage in depleted oil fields in the North Sea.
Other ports that could be relevant as export sites are all industrial ports. Especially ports that already handle gas, oil or other chemicals can more easily be retrofitted to handle $CO_2$ [GEUS, 2021], however, there are no other ports in Northern Jutland that handles these types of products. Furthermore, Axcelfuture [2022] mentions that smaller ports also should have the opportunity to have $CO_2$ vessels arrive at the port if smaller $CO_2$ amounts need to be shipped. This could for instance be *Skagen*, which is one of the industrial ports in Northern Jutland, and is therefore added as a sink.

### Sites for Utilization of CO2

Another sink for the $CO_2$ infrastructure is the actual sites for utilization in Northern Jutland. In this report, the point of departure is taken in the existing plans for projects that will utilize $CO_2$ to produce green methanol and other derivatives on the basis of $CO_2$ and hydrogen.
Current plans include the following projects:

| **Announced Projects** | **Corresponding $CO_2$ Demand** |
|---|---|
| Fjord PtX<br>SAF production at Nordjyllandsværket close to Aalborg<br>[The Danish Environmental Protection Agency, 2022] | 330,000 ton a year |
| Green CCU Hub Aalborg<br>Methanol production in Aalborg<br>[Green Hub Denmark, 2022] | 150,000 ton a year |
| Power2Met<br>Existing small demonstration plant producing methanol which in the future will produce up to 300,000 ton e-methanol a year<br>[GreenHub Denmark, 2020] | 410,000 ton a year |
| An energy island in Vesthimmerlands municipality will utilize local biogas and produce e-fuels<br>[Farsø Avis, 2022] | Unknown<br>Estimated to 296,000 ton a year based on average of other projects. |

**Table 7.1.** Announced PtX projects in Northern Jutland with a CO2 demand.

The map illustrated on figure 7.3 indicates the location of the potential $CO_2$ sinks in Northern Jutland. The location of the appointed ports for potential export is seen on the map as well as the potential PtX projects.

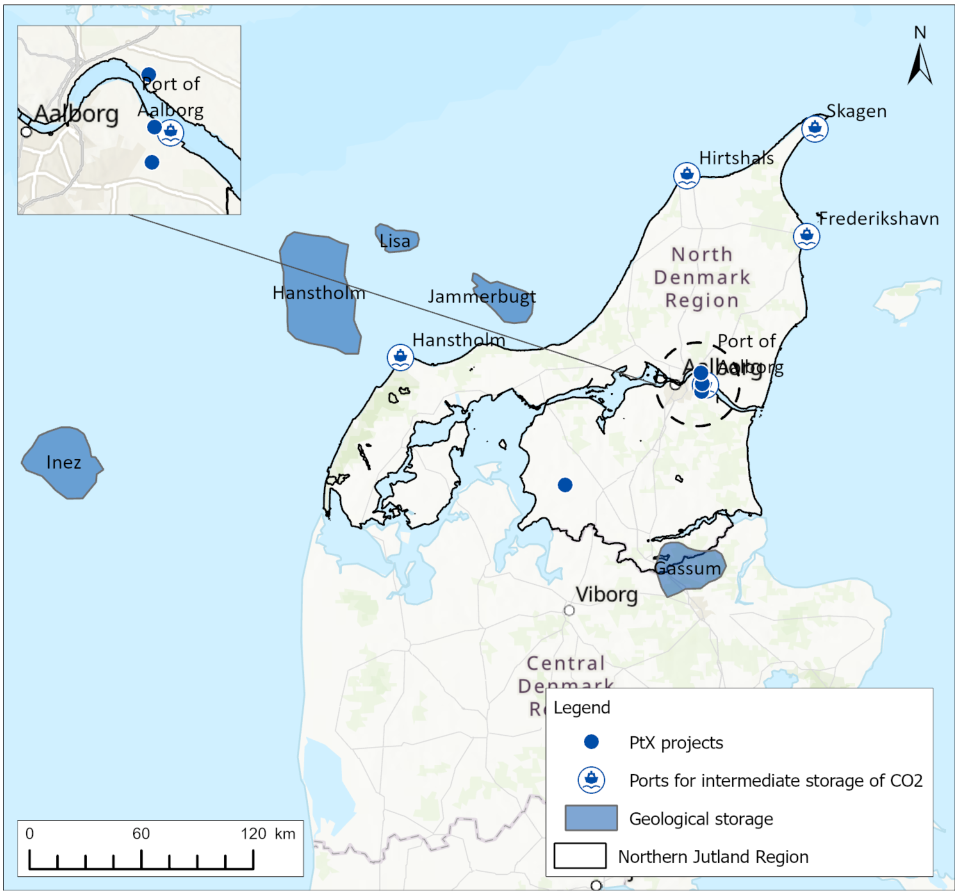


**Figure 7.3.** The location of $CO_2$ sinks.

The Inez structure for geological storage is located approx. 175 km from Hanstholm which is the nearest port, Lisa is 60 km away and Jammerbugt 55 km away from Hanstholm port, the Hanstholm structure is 30 km away from the port. For further analysis of the sinks, the geological storage of Hanstholm and Jammerbugt is chosen for the geospatial analysis since these are closest to Hanstholm port and Hirtshals port and thereby considers if both ports are to be utilized for embarkment in the future.

## 7.4 Scenario Methodology

In order to investigate different options for configuration of the CCUS infrastructure, the previous sections have provided a basis, by introducing the point sources, carbon capture technology and sinks, for setting up scenarios that can investigate the infrastructure. In that connection the following section describes the composition and the specific methodology of the scenarios.

### 7.4.1 Main Focus of the Scenarios

There are overall three main scenarios that investigate different sizes of the point sources which is:

A. Point sources > 1,000 t $CO_2$/year, based on current emissions
B. Point sources > 40,000 t $CO_2$/year, based on current emissions
C. Point sources > 10,000 t $CO_2$/year, based on emissions in 2045

These three different sizes of point sources are relevant to investigate since it can aid in understanding the feasibility of capturing and transporting $CO_2$ with different sources.

The $CO_2$ amount to be transported through the network is decided by the sinks. The PtX projects and their $CO_2$ demand is prioritized in all scenarios. The demand for the ports and onshore geological storage is based upon an equal distribution of what is left from the overall $CO_2$ emission.
The geospatial focus for the analysis of these scenarios of the $CO_2$ network in GIS is to follow the existing road network.
The visual representation of the three scenarios and their structure can be seen on figure 7.4.

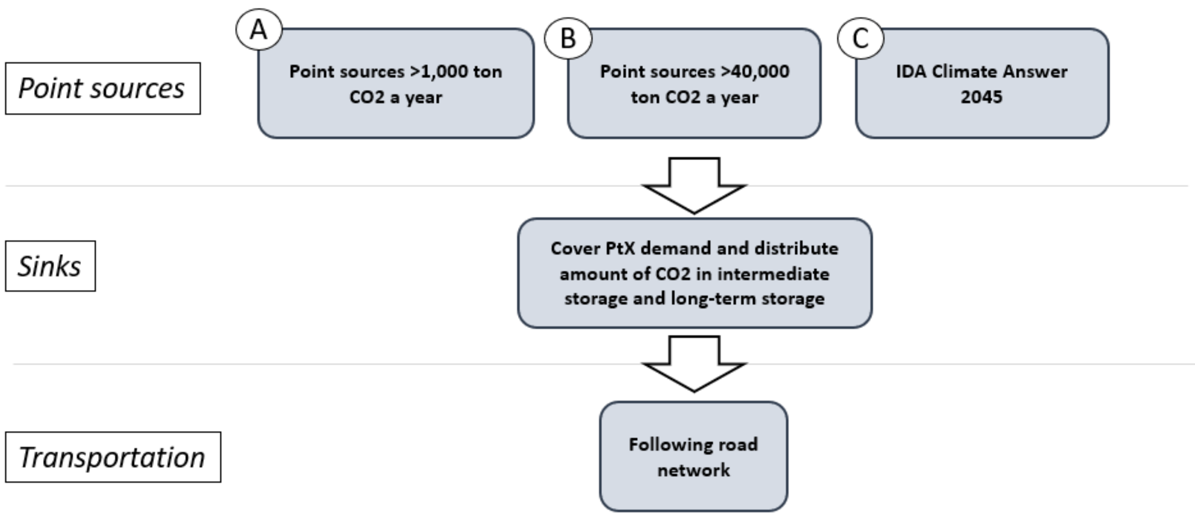


**Figure 7.4.** An overview of the point sources, sinks and transport focus for structure of scenarios.

The scenarios are investigated in a GIS methodology to further assess how these arrangements of the CCUS infrastructure impact spatially in Northern Jutland.

### 7.4.2 GIS Methodology

The input for the path planner tool is the dataset of the point sources, the road network and the sinks.
The tool is set up to include all point sources and sinks in one comprehensive network. This is done separately for all three scenarios, where the only varying input is the point source dataset.

The output from the path planner tool is a network that combines the point sources and sinks via network routes. The aim of this combined network is the overall shortest distances between the locations of point sources and sinks. Therefore, the quantity of $CO_2$ is not decisive for the network output from the tool.

### 7.4.3 Network Methodology

The amount of $CO_2$ that should be transported on the network routes from point source to sink is determined by matching the $CO_2$ demand of PtX facilities with the supply of $CO_2$ from point sources. Thereafter, surplus $CO_2$ is transported to ports and long-term storage. This knowledge is utilized to calculate what size of ship, truck or pipe that is needed for the specific section.
The capacity of the network routes are estimated based on the amount of $CO_2$ that is delivered from surrounding point sources and the sinks that the routes lead to.

To decide the amount transported on the actual routes, the point sources that are placed less than 1 km from the overall network of transportation are assumed to be able to connect to this, since it will be possible to vary the course of the pipeline from the road network or have short branch pipes that will have an insignificant impact on the overall economic considerations. Furthermore, truck transport would be redundant on the short routes. The capacity of the pipelines on the routes of the network is based on the t $CO_2$/h that is transported on each route – these are divided into three categories by The Danish Energy Agency [2021e], 10-30 t $CO_2$/h, 30-120 t $CO_2$/h and 120-500 t $CO_2$/h.
After this distinction between point sources, the ones who are left and have an emission below 15 t $CO_2$/h are assumed to have to transport $CO_2$ by truck since more than one truck in an hour will have an impact on the daily traffic in most areas. For each route with truck, a specific injection point on the pipeline is decided, to thereby assess the actual route the trucks will have to travel from point source to injection point. An intermediate storage is needed at each point source where the $CO_2$ will be transported by truck.
Each scenario is evaluated with different transport modes to the nearshore geological storage sites and is evaluated with either ship or offshore pipelines. This is evaluated to understand which mode of transportation is most feasible for the nearshore storage site. Transportation to the onshore storage site, Gassum, is evaluated with the same procedure as the other onshore sinks.

The input from GIS and the combined network are included in an economic evaluation.

### 7.4.4 Economic Methodology

The basic input for the economic evaluation is the cost of investments and O&M for each technology.

- **Capture unit:** Cost is based on amount of captured t $CO_2$/year.
- **Trucks:** Cost of trucks are based on length of routes and the amount of $CO_2$ that is transported yearly.
- **Onshore and offshore pipelines:** Cost is based on length of routes and amount of $CO_2$/hour.
- **Ships:** Cost of ships are based on amount of $CO_2$ that is transported every year.

- **Intermediate storage at point sources:** The storage capacity is based on a weekly discharge of the storage, and the cost is thus based on this size.
- **Intermediate storage at ports:** These storage facilities are based on the fact that one ship is located for each harbour with a capacity of 10,000 t $CO_2$. The loads are based on the necessary amount of cycles the ship must take to transport all $CO_2$ sent to the intermediate storage at the port. The cost is based upon the size of the loads.
- **Geological storage:** The cost is based on the total amount of $CO_2$ that is stored in a timeline of 30 years.
- **Scrap value:** For all technologies except geological storage, a scrap value equal to the investment cost is added.

As an input for the socio-economic evaluation, cost and income related to $CO_2$ is added in two ways. Firstly, it is added to the NPV calculation in the form of tax distortion. Since the $CO_2$ tax that companies would have to pay for emitting $CO_2$ is not applicable anymore, there is a missing tax income that would be found elsewhere – therefore, it is added as a socio-economic cost corresponding to the current $CO_2$ tax for companies which is between 16.7 €/t $CO_2$ for Aalborg Portland and 100.7 €/t $CO_2$ for the remaining companies [The Danish Ministry of Finance, 2022]. Both are multiplied by the tax distortion factor to include the socio-economic loss of taxes. Secondly, an income of capturing the $CO_2$ is added as a sale of $CO_2$ emission allowances. The income is 99.1 EUR/ton $CO_2$ and correlates with the expected socio-economic price of $CO_2$ emission allowances in 2030 [The Danish Energy Agency, 2022]. This means that the analysis includes both a socio-economic benefit of capturing the $CO_2$ and the loss of taxes the society would receive on the basis of the emitted $CO_2$.

# Spatial and Economic Evaluation 8

The aim of this chapter is to explore the results of different ways of arranging a CCUS infrastructure. The scenarios described in the previous section are examined both spatially and economically, to determine their technical and spatial feasibility and influence on cost.

The chapter includes a description of each scenario and the spatial impact its network has in terms of location of routes, and how many kilometres of pipe, truck or ship transport it entails. The economic evaluation is based on this information from the previous chapter and the input and the economic input detailed in appendix A and this chapter contains both socio-economic calculations as well as the yearly costs for each scenario, and the cost per ton of $CO_2$.

## 8.1 Scenario A – Point Sources > 1,000 t $CO_2$ a year

The main aspect of this scenario is the selection of point sources with emissions above 1,000 ton $CO_2$ a year. This creates a more comprehensive network of sources, since more is included compared to the other scenarios.

### 8.1.1 CCUS Infrastructure of Scenario A

The spatial result of the CCUS infrastructure in scenario A is shown in figure 8.1.

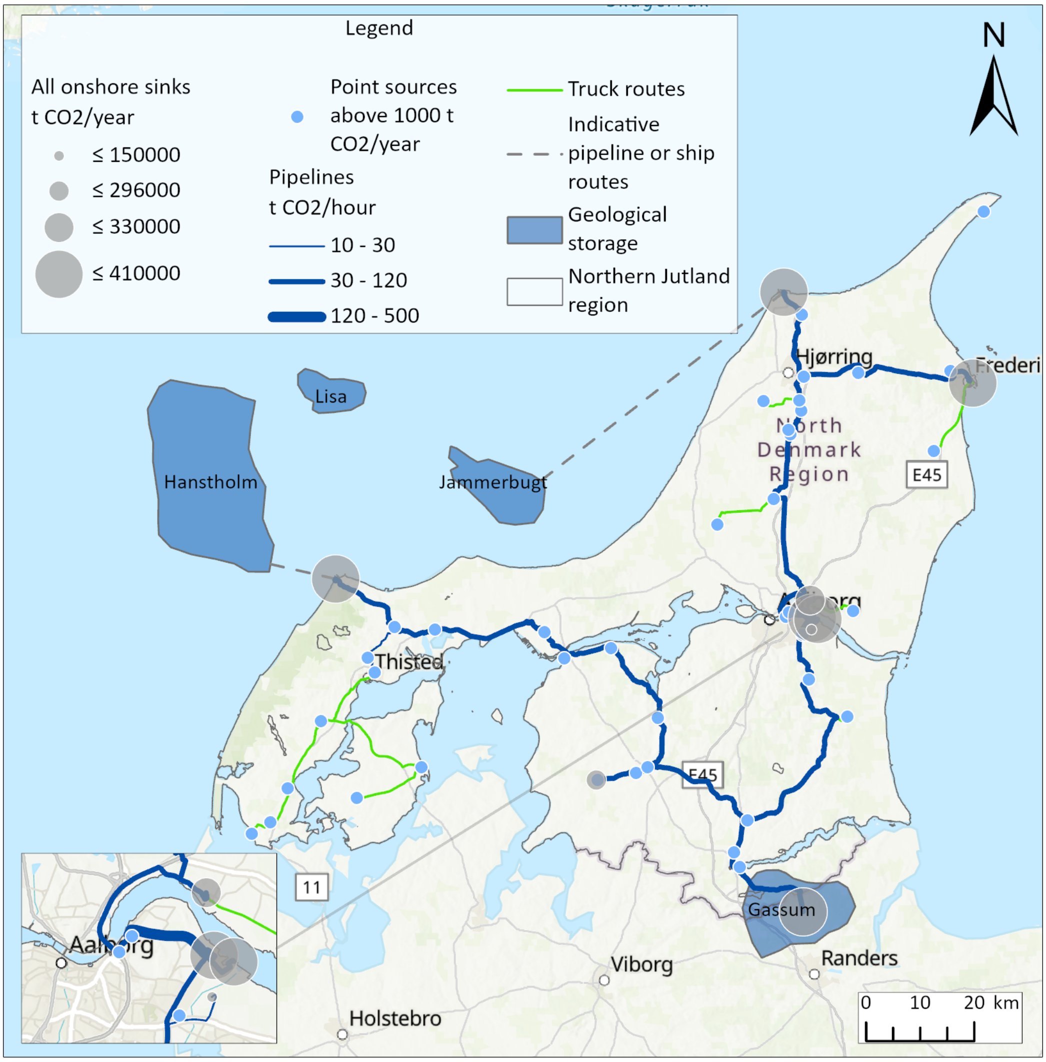


**Figure 8.1.** $CO_2$ network with point sources above 1000 t $CO_2$/year.

The components of the CCUS infrastructure in scenario A are described in the following:

1. 3.2 mil. t $CO_2$/year is captured in this scenario.

2. The input for the path planner tool in GIS has produced the network shown in figure 8.1. The total network for transport for point sources above 1,000 t $CO_2$ a year is 537.9 km. 360 km of this is pipeline transport and the total km transport by truck is 264 km which is based on individual truck routes from point source to injection point on the pipeline. The routes to nearshore geological storage add 71.7 km to either pipeline length or ship. The network consists of pipeline running north/-south between Hirtshals, Aalborg and Gassum/Hobro and west/southeast between Hanstholm and Gassum. The pipeline is not placed in a straight line between these points, as there are deviations where larger point sources and sinks are connected. The rest of the system consist of truck routes that are connected to the network by injection point at different locations on the pipeline system. For the truck routes on Mors, the routes are not the shortest routes since they are based on the initial network and thus overlap.

3. The sinks are appointed an amount of $CO_2$. This is for the PtX projects equivalent to the amount of $CO_2$ they need to produce e-fuels. The remaining $CO_2$ is divided between the sinks, which means that equal amounts are sent to both Gassum storage, nearshore geological storage and the ports for intermediate storage which is 402,000 ton $CO_2$ a year. Skagen port is an unusual sink as there is only one point source near this sink and therefore the sink only receives $CO_2$ from this source. The $CO_2$ quantity sent to the sinks are shown in table 8.1.

| **Sink** | **$CO_2$ amount (t $CO_2$/year)** | **PtX projects (Sink)** | **$CO_2$ amount (t $CO_2$/year)** |
|---|---|---|---|
| Hirtshals Port | 402,000 | CCU Hub Aalborg | 150,000 |
| Hanstholm Port | 402,000 | Vesthimmerland | 296,000 |
| Aalborg Port | 402,000 | Fjord PtX | 330,000 |
| Frederikshavn Port | 402,000 | Power2Met | 410,000 |
| Skagen Port | 7,000 | | |
| Gassum onshore storage | 402,000 | | |

**Table 8.1.** $CO_2$ demand of each sink for scenario A.

### 8.1.2 Socio-Economic Results of Scenario A

In scenario A, the amine capture units are used on all point sources except biogas plants, as they are expected to have invested in these units beforehand. The yearly costs for the capture plants are the highest expense in the scenario that total to around ~109 mil. €/year – the yearly costs for capture units are displayed in figure 8.2.

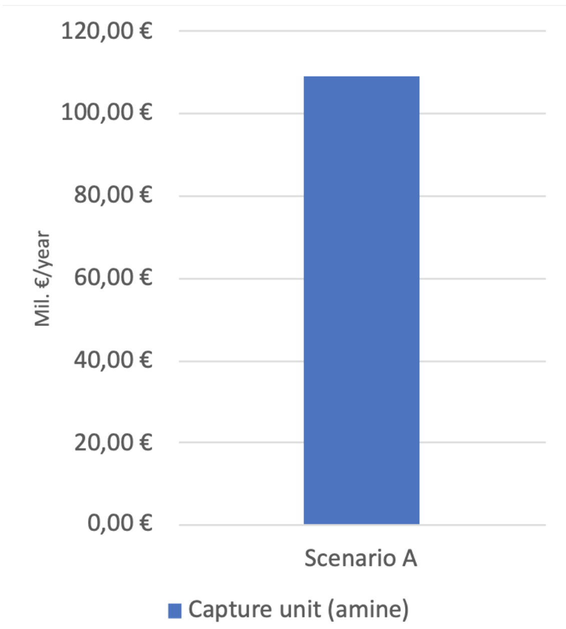


**Figure 8.2.** Yearly costs for CC plants in scenario A.

As shown on the map in figure 8.1, the onshore transportation routes consist of both onshore pipeline and truck transport. The point sources that are connected via truck routes need an intermediate storage in order to be able to store $CO_2$ temporarily until a truck can collect it. Furthermore, the intermediate storage facilities are used when the $CO_2$ is delivered from point sources to a harbour. This means that when trucks are used for transportation, the cost of intermediate storage is also increased – the yearly costs for transport are shown in figure 8.3.

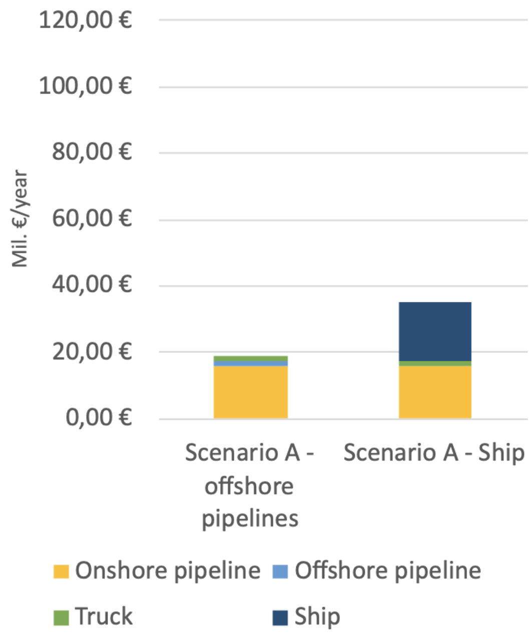


**Figure 8.3.** Yearly costs for transportation of $CO_2$ in scenario A.

In scenario A, the transport costs that consist of trucks, ships and pipelines change depending on if the offshore transport is done using ship or offshore pipelines, whereas the use of offshore pipelines add a yearly cost of 1.5 mil €/year, the ship add a cost of approximately 18 mil. €/year. Therefore, the cheapest option for offshore transport in this case is using offshore pipelines. This result might change if there are modifications in the distance the $CO_2$ is transported, since the cost of offshore pipelines depend on this. This indicates that ship transport is more economically feasible when transporting $CO_2$ over longer distances - this could for instance be to an offshore storage or to other countries.

Finally, the costs for onshore and nearshore storage are also included along with intermediate storage. The cost of onshore and nearshore storage depend on their size - the size is determined by the amount of $CO_2$ that would be sent to the storage every year. In these scenarios, it is assumed that the storage points only receive $CO_2$ from Northern Jutland - this might not be a realistic assumption as the storage facilities can receive $CO_2$ from other parts of the world or from other parts of Denmark. However, in this analysis, only the costs for the amount of $CO_2$ sent from Northern Jutland's point sources are covered. If other actors from the rest of Denmark or Europe were to supply the storage with $CO_2$, the costs of the nearshore and onshore storage could be lowered due to the costs being distributed and wider spread across the market.
As can be seen in figure 8.4, the cost for intermediate storage at ports have the largest yearly cost. The cost for these are higher than the intermediate storage at CC plants

because the port intermediate storage have higher capacities as they are filled and emptied with all the 402,000 t $CO_2$ that is transported to and shipped from the four ports. The reason why the nearshore and onshore storage have lower yearly costs even though their capacities are higher, is due to the fact that the scrap value for all technologies have been included in the yearly cost for all technologies except for the permanent onshore and nearshore storage sites that are expected to be placed permanently.

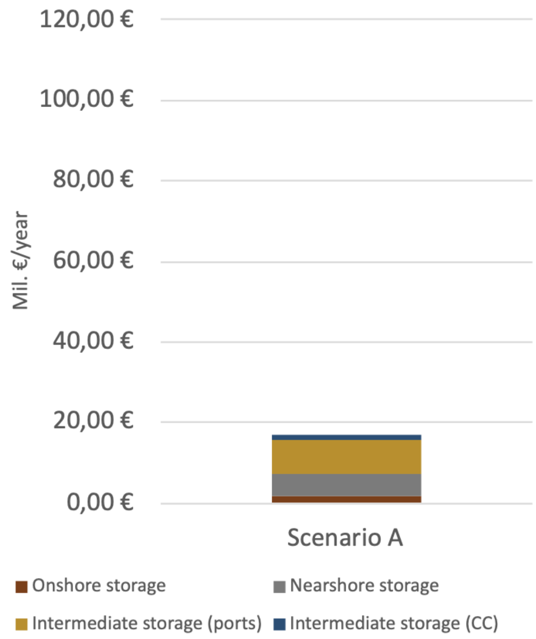


**Figure 8.4.** Yearly costs for storage in scenario A.

The socio-economic results are for each scenario divided into one NPV calculation for the scenario where ships are used as transport for nearshore storage and one where offshore pipelines are used. The results of the NPV calculation for scenario A can be seen in figure 8.5, where it is evident that the scenario including ship transport is not an economically feasible solution, given the high costs for ship transport on relatively short distances. Therefore, ship transport is not considered for any further evaluation of this scenario.

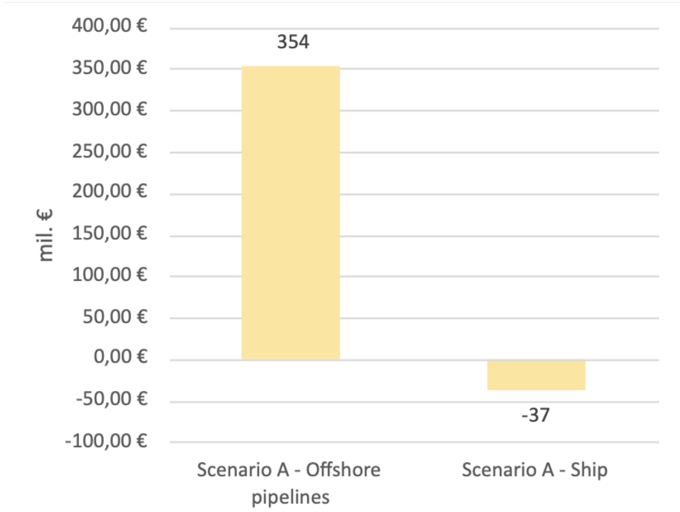


**Figure 8.5.** NPV results for scenario A.

It is however evident, that scenario A with offshore pipelines is an economically feasible scenario because of the positive NPV value, where the investment is paid off by the income from sale of $CO_2$ emission allowances.

## 8.2 Scenario B – Point sources > 40,000 t $CO_2$ a year

The main aspect of this scenario is the selection of point sources with emissions above 40,000 t $CO_2$ a year to provide the basis for the network.

### 8.2.1 CCUS Infrastructure of Scenario B

The spatial result of the CCUS infrastructure is shown on figure 8.6.

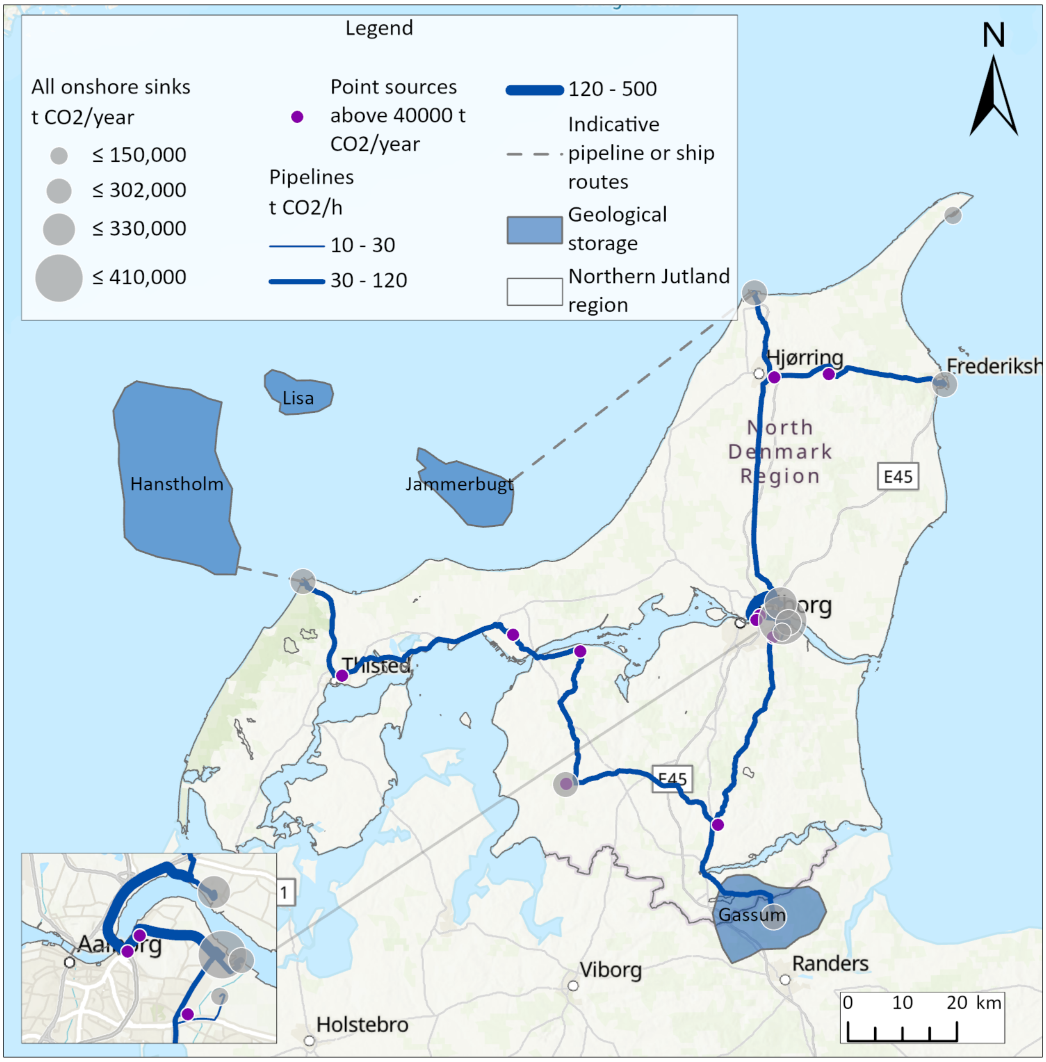


**Figure 8.6.** $CO_2$ network with point sources above 40,000 t $CO_2$/year.

The components of the CCUS infrastructure in scenario B are described in the following:

1. 2.7 mil. t $CO_2$/year is captured in this scenario.

2. The input for the path planner tool in GIS and has produced the network shown in figure 8.6. There are no minor point sources meaning that this scenario is only configured by pipeline transport between point sources and sinks. The total network for transport of $CO_2$ with point sources above 40,000 t $CO_2$ a year is 334.6 km. The routes to nearshore geological storage add 71.7 km to either pipeline length or ship. The network consists of a main network connected by pipelines, where only larger point sources are included. This means that the system roughly goes north/south and west towards Hanstholm port and east towards Frederikshavn port.

3. The amount of $CO_2$ transported to the PtX projects does not change from scenario A, as this is still based on the equivalent $CO_2$ demand for the e-fuel production. The remaining $CO_2$ is divided between the sinks, which means that equal amounts are sent to both Gassum storage, nearshore geological storage and the ports for

intermediate storage which is 302,000 ton $CO_2$ a year. Skagen Port is not included in this scenario since no point sources are nearby and there is therefore no connection in the network to this sink. The $CO_2$ quantity sent to the sinks are shown in table 8.2.

| **Sink** | **$CO_2$ amount (t $CO_2$/year)** | **PtX projects (Sink)** | **$CO_2$ amount (t $CO_2$/year)** |
|---|---|---|---|
| Hirtshals Port | 302,000 | CCU Hub Aalborg | 150,000 |
| Hanstholm Port | 302,000 | Vesthimmerland | 296,000 |
| Aalborg Port | 302,000 | Fjord PtX | 330,000 |
| Frederikshavn Port | 302,000 | Power2Met | 410,000 |
| Gassum onshore storage | 302,000 | | |

**Table 8.2.** $CO_2$ demand of each sink for scenario B.

### 8.2.2 Socio-Economic Results of Scenario B

In scenario B, the setup of capture plants are equal to scenario A, where the cost of capture plants on biogas plants is not included. However, as there are fewer point sources in this scenario, the yearly costs are subsequently lower compared to scenario A. These are displayed in figure 8.7, where it can be seen that the combined yearly costs for CC plants are approximately 8.5 mil. €/year lower in scenario B compared to scenario A.

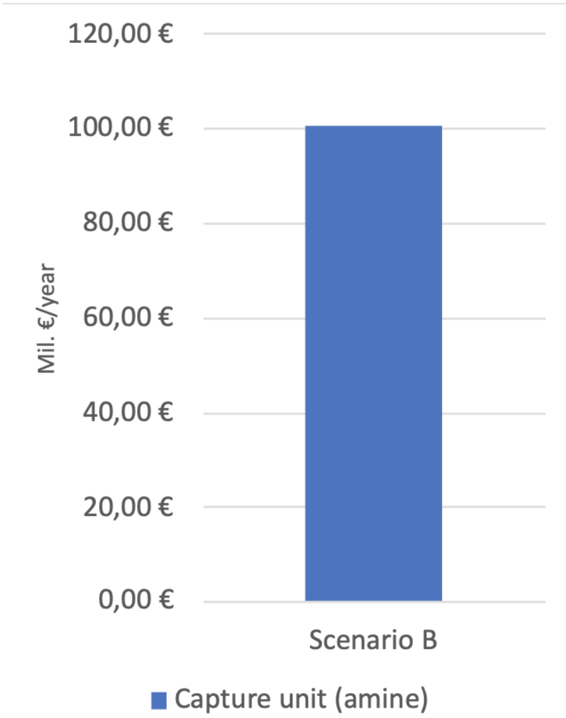


**Figure 8.7.** Yearly costs for CC plants in scenario B.

Even though the amount of point sources are lowered significantly in this scenario, the costs are not lowered equally since the remaining point sources have significant $CO_2$ emissions

and therefore still require large costs for CC plants – furthermore, the main expense, ie. the CC plant for Aalborg Portland remains unchanged which is 41.7 mil. €/year compared to the total of 49.7 mil. €/year. When the scrap value for the CC plants is added to the yearly costs, the total is ~100 mil. €/year.
When only the larger point sources are included, several biogas plants are excluded from the network, even though they already have made the investment of capture plants. If these were to be included, they would thus not have any effect on the cost of the capture plants, which are the largest yearly cost of the scenarios. This raises the question of if the cut-off value should be equal across all point sources or tailored to the individual type. Biogas plants can thus be perceived as accessible components in the infrastructure, that can be more easily included in the infrastructure because of its existing capture units.

In scenario B, truck routes are not included and the only onshore transportation mode is via onshore pipelines. The total length of transportation routes are thereby shorter, since there is no transport from the smaller point sources that were included in scenario A. The yearly costs for onshore pipeline are lowered from 15 to 10 mil. €/year and the offshore pipeline cost drops because less $CO_2$ is sent out via pipes. The cost for ship transport remain the same as in scenario A, since the same length of route and approximately the same size of ship is being used, and the cost of this is not dependent on the amount of $CO_2$ that is transported to nearshore storage. The transport costs are shown in figure 8.8.

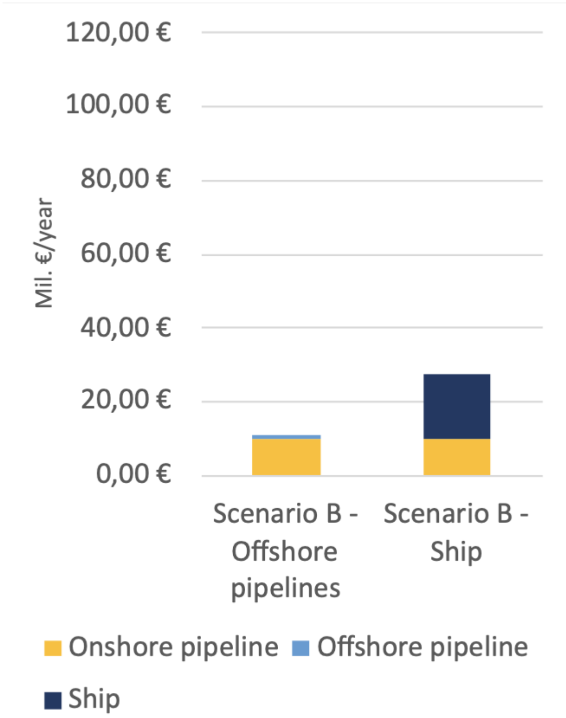


**Figure 8.8.** Yearly costs for transportation of $CO_2$ in scenario B.

Because of the absence of trucks in this scenario, the need for and cost of intermediate storage at carbon capture plants is also removed. This causes a small reduction in the cost for the combined storage facilities. There are also small reductions in costs for onshore and nearshore storage facilities, because a smaller amount of $CO_2$ is injected at these locations, whereas the largest reduction of ~1.5 mil. €/year is seen in the nearshore storage cost.

The costs for storage elements are illustrated in figure 8.9.

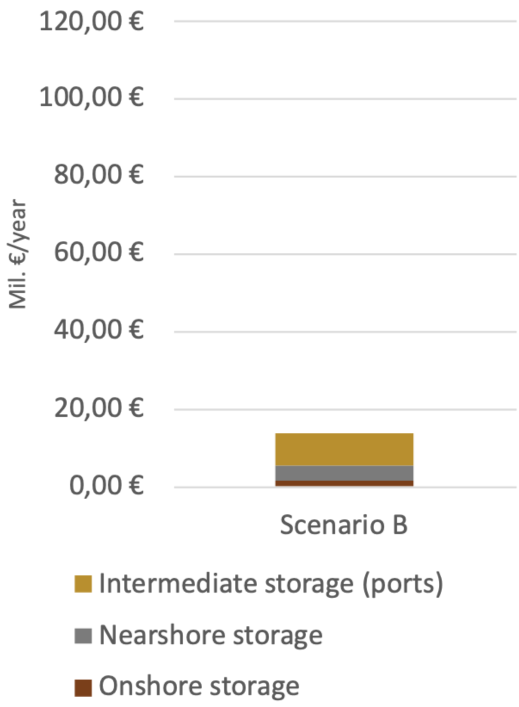


**Figure 8.9.** Yearly costs for storage in scenario B.

In the NPV results for scenario B that are shown in figure 8.10, it can be gathered that scenario B with a NPV of 894 mil. € is more economically favourable compared to scenario A with a NPV of 354 mil. €, both when the offshore transport is via offshore pipelines and by ship.

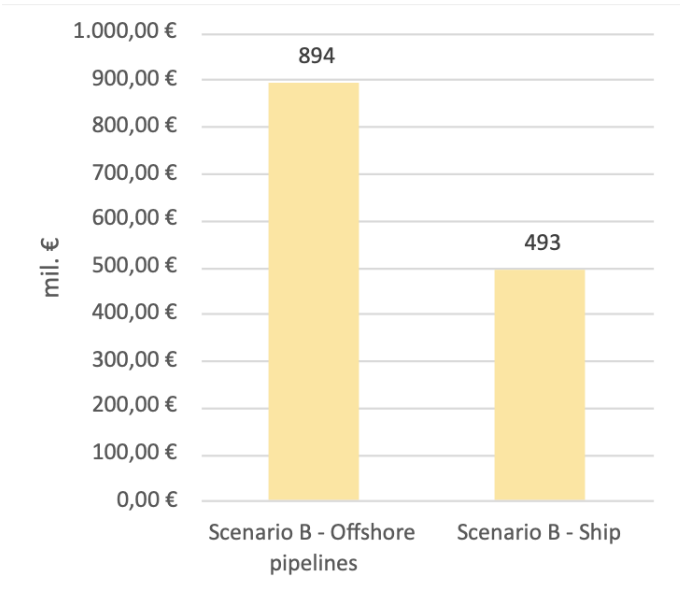


**Figure 8.10.** NPV results for scenario B.

The reason why this scenario has higher NPV values is because the yearly costs in total are lower, but there is still a high amount of $CO_2$ that is captured and therefore the sale of $CO_2$ emission allowances ensure a higher income in the scenario. The results still show that the investment in ship transport is less economically favorable compared to offshore pipelines. Therefore, ship transport is not considered for any further evaluations of this scenario.

## 8.3 Scenario C – IDA's Climate Answer 2045

The main aspect of Scenario C is the selection of point sources based on the IDA Climate Answer 2045 projections, and thus means that this scenario varies from the two previous ones. This is mainly due to the fact that the expected amount of $CO_2$ to capture from industries is decreased and that the expected amount of $CO_2$ from biogas upgrading is increased. This scenario is meant as a showcase of the future perspective, and to see if investments should be made to fit the future demands instead of possibly overdimensioning investments because they are tailored to current conditions. This thereby gives an opportunity to compare the scenarios on deviations and similarities.

### 8.3.1 CCUS Infrastructure of Scenario C

The spatial result of the CCUS infrastructure in scenario C is shown in figure 8.11.

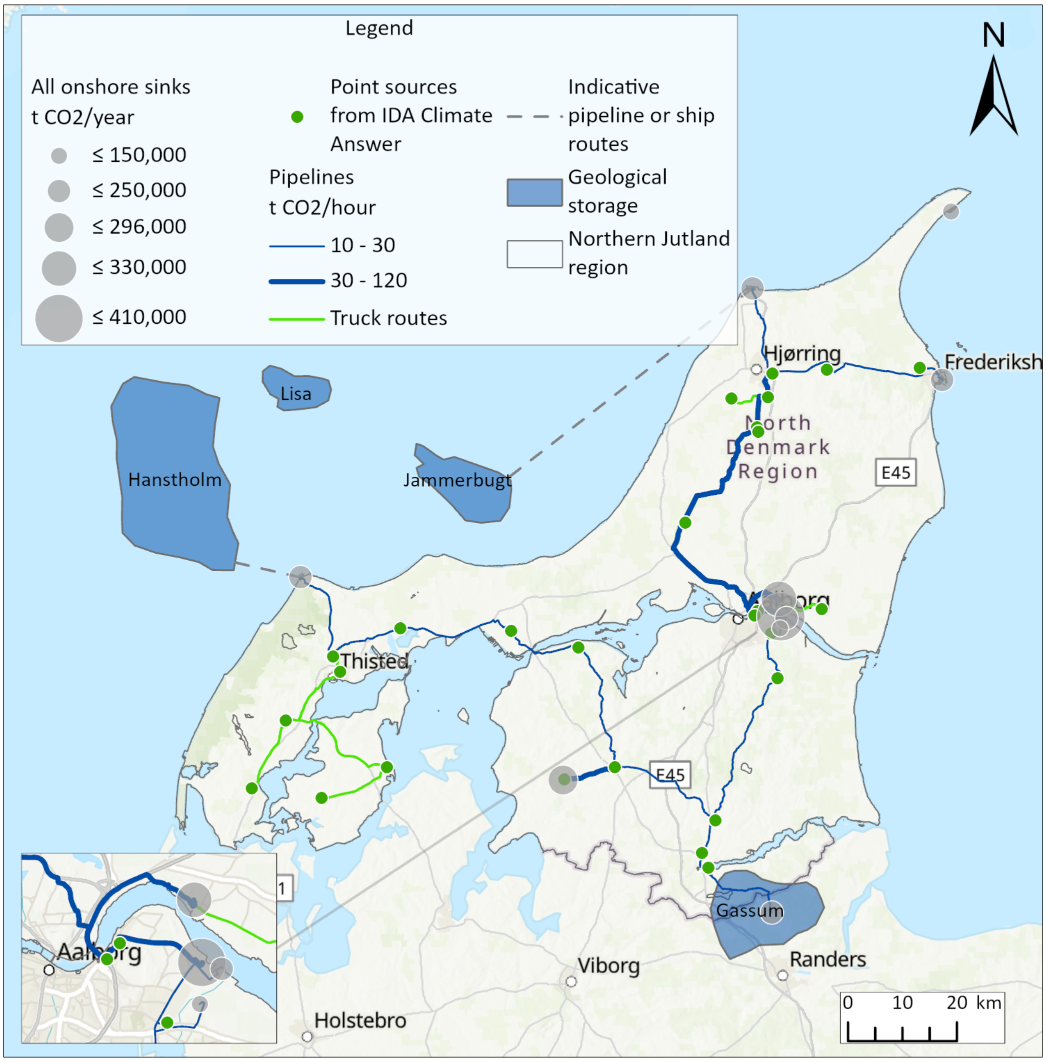


**Figure 8.11.** $CO_2$ network with point sources based on IDA's Climate Answer 2045.

The components of the CCUS infrastructure in scenario C are described in the following:

1. 2.5 mil. t $CO_2$/year is captured in this scenario.

2. The input for the path planner tool in GIS has produced the network shown in figure 8.11. The total network for transport of $CO_2$ with point sources based on IDA's Climate answer is 487.7 km. 359 km is pipeline transport and the combined truck routes are 339 km, where some of the km overlap. The routes to nearshore geological storage adds 71.7 km to either pipeline length or ship. The network of Scenario C resembles the other scenarios to a large extent, especially scenario A, however this scenario deviates on the route going north/south between Hirtshals and Aalborg since a larger point source is located on this path.

3. The $CO_2$ quantity sent to the sinks are shown in table 8.3. The PtX projects are also prioritized in this scenario and the amount of $CO_2$ sent to these sinks is the equivalent $CO_2$ demand based on the production of e-fuels. The remaining accumulated $CO_2$ from the point sources is divided and sent to the rest of the sinks.

| Sink | $CO_2$ amount ($t\ CO_2$/year) | PtX projects (Sink) | $CO_2$ amount ($t\ CO_2$/year) |
|---|---|---|---|
| Hirtshals Port | 250,000 | CCU Hub Aalborg | 150,000 |
| Hanstholm Port | 250,000 | Vesthimmerland | 296,000 |
| Aalborg Port | 250,000 | Fjord PtX | 330,000 |
| Frederikshavn Port | 250,000 | Power2Met | 410,000 |
| Gassum onshore storage | 250,000 | | |

**Table 8.3.** $CO_2$ demand of each sink for scenario C.

### 8.3.2 Socio-Economic Results of Scenario C

The final scenario also includes amine CC plants for all point sources except biogas producers. Since the point of departure of this scenario is set in 2045, the general $CO_2$ emissions from most point sources are lower, which thereby lowers the cost for CC plants – in this scenario the costs for CC plants is ~60 mil. €/year. Comparing these to scenario A, the costs for CC plants in Scenario C are almost half the cost in Scenario A. If an investment is made in CC plants according to scenario A, this would mean that several of the plants would be over scaled compared to the future demand for $CO_2$ transport, or that they would be closed down. This depends on the years where the plant would be connected to the network, in order to determine if this would be feasible nevertheless. The yearly costs for CC plants are shown in figure 8.12.

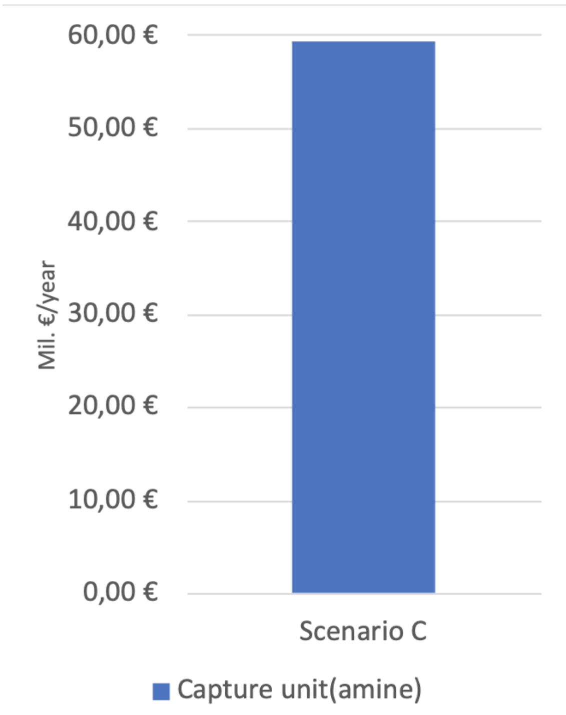


**Figure 8.12.** Yearly costs for CC plants in scenario C.

In this scenario, the amount of pipelines are increased compared to scenario B, since more point sources are included, but is more or less equivalent to scenario A in the design of the pipelines. Because there is a lower total amount of $CO_2$ that is being transported in this scenario, the majority of the pipes that are being used are also smaller. The cost for onshore pipelines in this scenario are approximately 13 mil. €/year, which is ~2 mil. €/year lower compared to scenario A. These can be seen in 8.13.

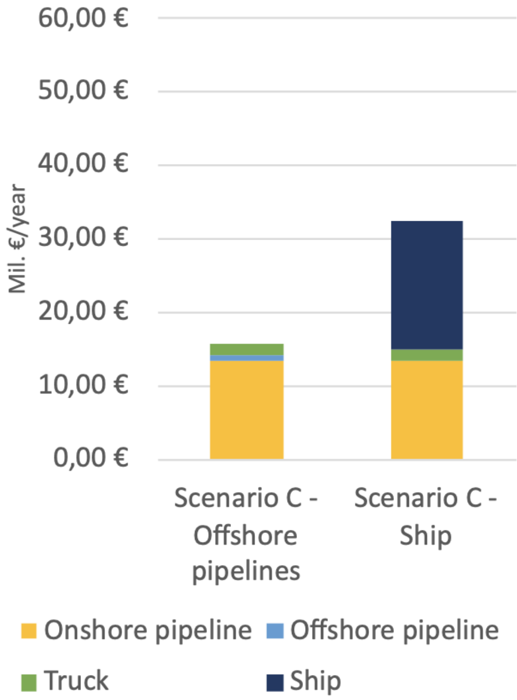


**Figure 8.13.** Yearly costs for transportation of $CO_2$ in scenario C.

Trucks are again included in this scenario, to transport $CO_2$ from smaller point sources to injection points. As the combined truck routes are shorter, there is a small reduction in this cost compared to scenario A.

In scenario C, the cost for intermediate storage is increased compared to scenario B, as trucks involve the need for intermediate storage at certain CC plants. The cost for intermediate storage both at ports are higher compared to scenario A because the storage is slightly larger. The cost for intermediate storage at CC plants is higher than in scenario A, because of the higher amounts of $CO_2$ that are sent from biogas plants in 2045. The storage costs are illustrated in figure 8.14.

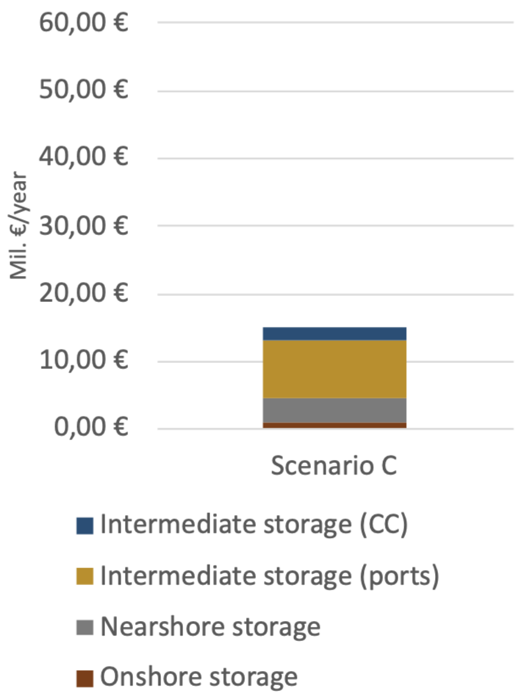


**Figure 8.14.** Yearly costs for storage in scenario C.

Scenario C is the scenario with the lowest overall NPV values, which are shown in figure 8.15. Both the scenario with offshore pipelines and with ships show to be economically unfeasible scenarios. Most significant change in this scenario, is the lower amount of $CO_2$ that is captured and transported. This implies that the amount of $CO_2$ that is captured, and thus the amount of $CO_2$ emission allowances that can be sold are not enough to compensate for the costs of investment and O&M, even though this scenario has the lowest yearly costs.

Again, the NPV value for the scenario including ships is lower than for the one with offshore pipelines, indicating a lower economical feasibility. Therefore, ship transport is not considered for any further evaluation of this scenario.

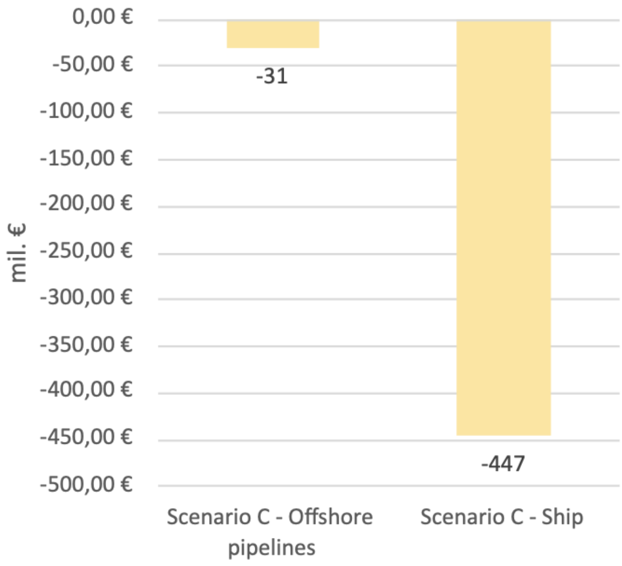


**Figure 8.15.** NPV results for scenario C.

Scenario C can be used to give an indication of what costs that would be present, if the investments that are made now are adjusted to the future expected $CO_2$ emission.

## 8.4 Comparison of Scenarios

In total, six scenarios have been investigated in this section and the scenarios with ship transport to nearshore geological storage are excluded from further evaluation since they are less economically feasible because of the relatively short distance to the nearshore storage. Therefore, this section only contains one type of scenario for scenario A, B and C, which is where offshore pipelines are used for the offshore transport.

In each scenario, the yearly costs for investment and O&M for each technology have been presented. In figure 8.16, the combined costs are shown for each scenario, and underline the significance of the costs for the CC plants, which are the decisive factor that determines which scenario has the lowest costs. This means that the scenario with the lowest amount of $CO_2$ that is captured, will have the lowest yearly costs in total.

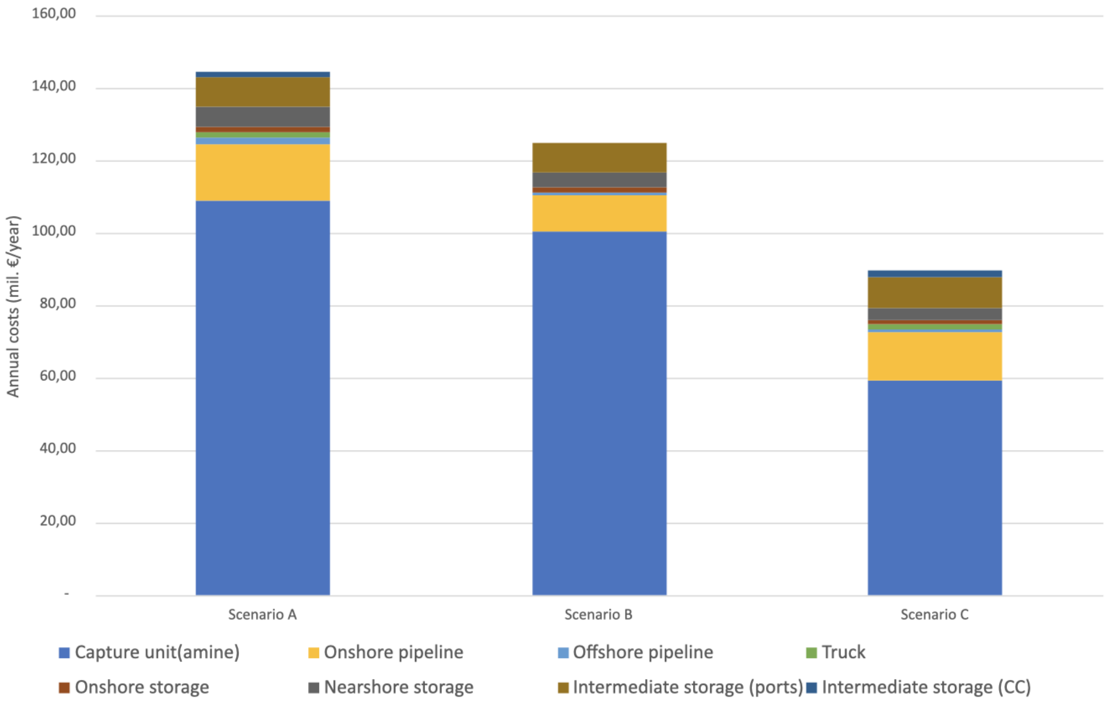


**Figure 8.16.** Results of yearly costs of each scenario.

In order to further compare the scenarios, the cost per ton $CO_2$ is calculated. This is done based on the numbers from the previous figure, to compare the annuity of the investment together with the related O&M of each technology with the amount of $CO_2$ that is captured, transported or stored via each technology. The division of the costs can be seen on figure 8.17.

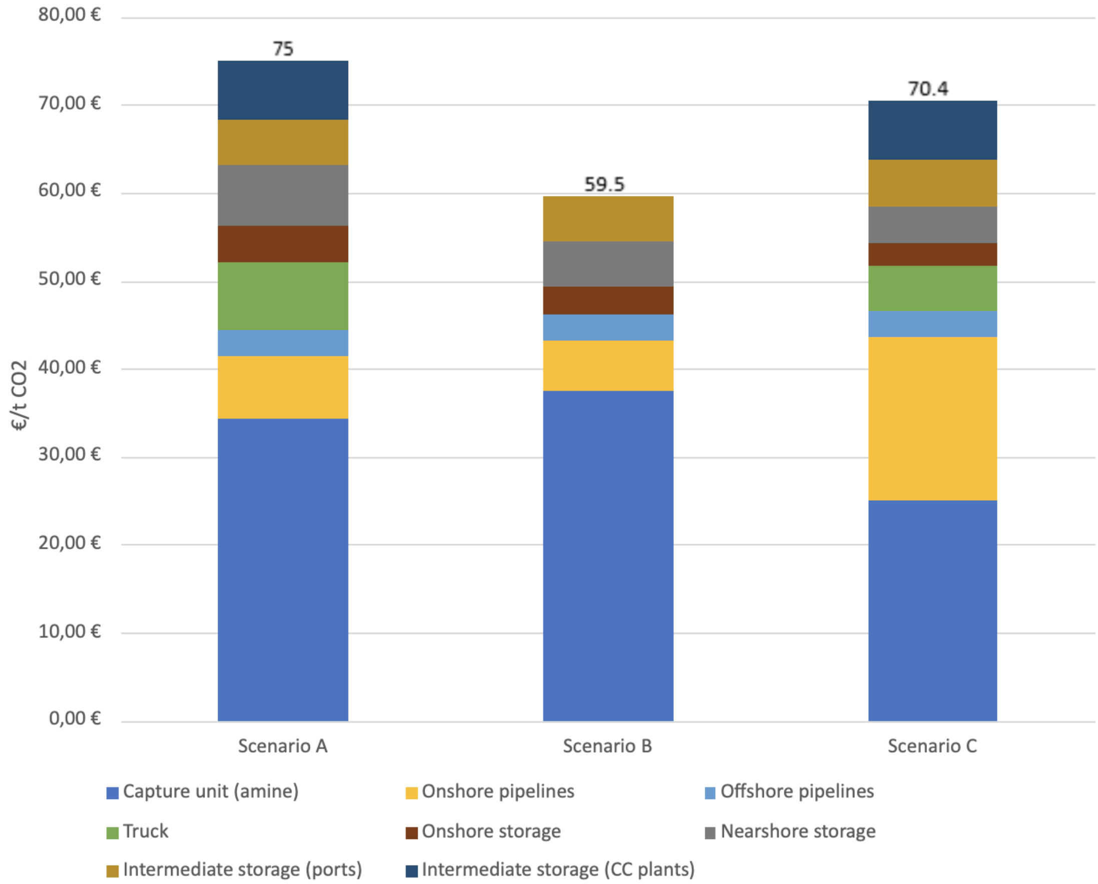


**Figure 8.17.** Costs per ton $CO_2$ of the scenarios.

It is evident that scenario B has the lowest total cost per ton $CO_2$ at 59.5 EUR/t $CO_2$ and is therefore the most feasible scenario based on the economic evaluation. Even though the scenario has the highest cost/t $CO_2$ for the CC plants, the scenario does not include intermediate storage at CC plants and trucks, which has a significant effect in the combined cost/ t $CO_2$. Furthermore, the cost/t $CO_2$ for onshore pipelines are lower in this scenario, both because the scenario has the lowest yearly costs for pipelines, but also because the amount of $CO_2$ that is sent through is relatively high compared to the cost. Scenario C has the second lowest cost/t $CO_2$ at 70.4 EUR/t $CO_2$. A significant factor to this result is the high cost/t $CO_2$ for the onshore pipelines. The costs for onshore pipelines in scenario C is 3.5 mil. €/year higher than in scenario B, and the amount of $CO_2$ that is sent through is lower – this results in a higher cost/t $CO_2$ which increases the scenario's total cost/t $CO_2$. Scenario A has the highest cost/t $CO_2$, at 75 EUR/t.
In chapter 4, some costs pr. ton $CO_2$ are mentioned. It is however not relevant to compare these to the found costs/t $CO_2$ of these scenarios since additional input are used for this report's economic evaluation, such as capture units and scrap costs.

In each scenario, the total yearly costs for each scenario has been presented. These are the input for investment and O&M that are used for the NPV calculation. Furthermore, the cost and income for $CO_2$ is used to calculate the NPV. In figure 8.18, the combined yearly input and output for each scenario are shown, divided into the investment costs, the O&M costs, the distortion of $CO_2$ tax, and finally, the income for sale of $CO_2$ emission allowances.

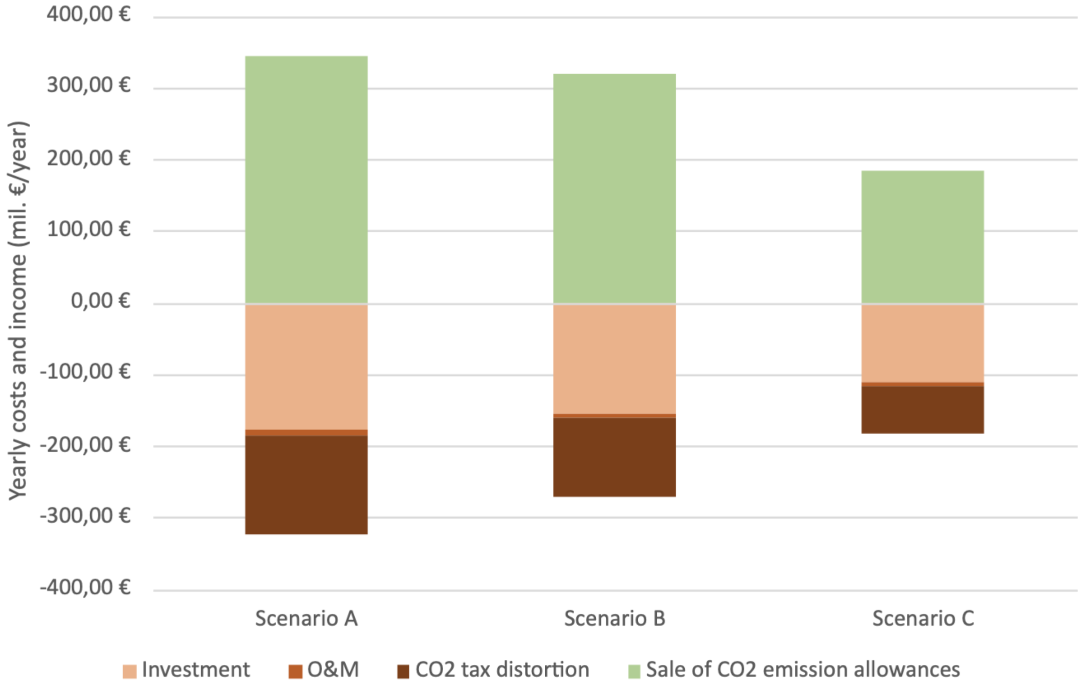


**Figure 8.18.** Input of yearly costs and income in NPV calculation of each scenario.

These explain why the NPV results for the scenarios are negative or positive. In Scenario A and B, the income is higher than the costs, which result in positive NPV values, respectively at 354 and 894 mil. EUR. In Scenario B, the sale of emission allowances are relatively higher than the costs, compared to Scenario A, which is why the NPV is more positive for Scenario B. In Scenario C, the sale of emission allowances do not make up for the costs, and therefore the NPV result is negative, at -31 mil. EUR. The difference between income and costs in Scenario C is 1.65 mil. €/year, indicating that minor modifications in these costs or the income can affect the feasibility of this scenario.

The NPV results of these scenarios are shown in figure 8.19 and shows that Scenario B is the scenario with the highest NPV, and thereby the most economically attractive scenario that will have the highest income based on the investments costs.

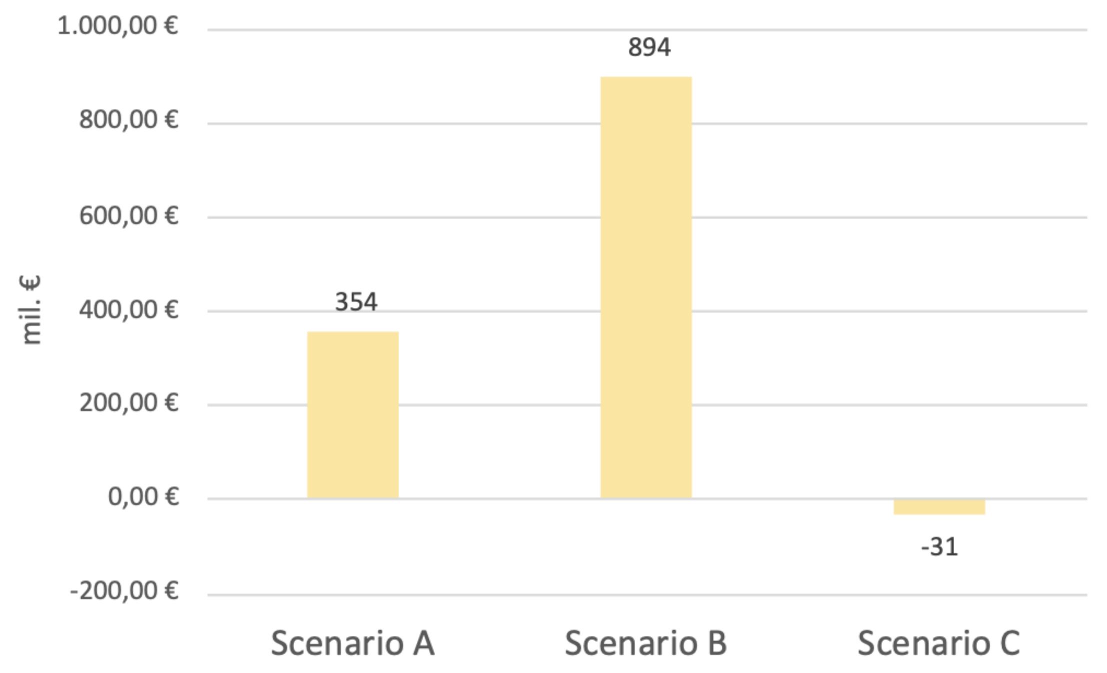


**Figure 8.19.** Results of NPV calculation of each scenario.

This shows that even though more $CO_2$ is captured in scenario A, the higher yearly costs of especially the onshore pipeline, because of the additional point sources, make a difference when determining the feasibility of the scenario. This result shows that capturing $CO_2$ from the point sources with the highest emissions is more feasible than capturing from all point sources above 1,000 t $CO_2$/year. This might also be impacted by the location of the minor point sources in the network, where the cost of pipeline length to transport the $CO_2$ potentially outweigh the benefits of capturing it. Overall, the results from scenario C show that customizing the infrastructure to the future $CO_2$ potential is not a feasible socio-economic solution in 2030. This is because the amount of captured $CO_2$ is low enough, so that the sale of emission allowances do not make up for the investment and O&M costs. The emissions of scenario C is set in 2045 and thus do not show the path from current emissions to this level, which could mean that the scenario is feasible during the 15 years between 2030 and 2045. Furthermore, the difference to when the scenario could become feasible is relatively low at 1.65 mil €/year and could easily be circumvented by other circumstances such as changes in the economic components.
The results have however shown that it is still feasible also to include the smaller point sources, proving that these could be included in a combined CCUS network.

There are many uncertainties of the technical costs and the items of the scenarios such as pipeline length. The uncertainties in this economic evaluation are further examined in the following sensitivity analysis.

## 8.5 Sensitivity Analysis

This section seeks to investigate if uncertainties in the input parameters in the economic evaluation have an effect on the output of the NPV results, and on the scenarios' cost/t

$CO_2$, and thereby which scenario is the most feasible.
It is relevant to highlight certain input parameters to investigate what impacts the results, and thereby which elements of the CCUS infrastructure have a substantial impact on the implementation and thereby development of CCUS in Northern Jutland.
An overview of the changes that are investigated and the reasoning behind are represented in table 8.4.

| Changes in input parameter | Reasoning | Change (decrease) | Change (increase) |
|---|---|---|---|
| Pipeline length | The pipeline length is investigated due to changes in pipeline routes and uncertainty of which point sources are connected | -20% | +20% |
| Investment costs | There is a general uncertainty of future costs of the investments in the CCUS technologies. Therefore, this uncertainty is investigated through high and low numbers of each technology from the The Danish Energy Agency [2021e] The exact input can be found in appendix A.10 | Low | High |
| Discount rate | To investigate the discount rate impact of technologies with a longer lifetime, this is lowered according to rates by The Danish Ministry of Finance [2021] | 1.5% and 2.5% | |
| $CO_2$ emission allowances | The future price of $CO_2$ emission allowances is highly uncertain and is therefore investigated [The Danish Energy Agency, 2022] | 79.3 €/ton $CO_2$ | 204 €/ton $CO_2$ |

**Table 8.4.** Changes that are investigated in the sensitivity analysis.

### 8.5.1 Pipeline Length

The routes provided by the GIS analysis that constitute the $CO_2$ network in the three scenarios are following the road network which to some degree is valid. However, there will be instances where the routes will change since other structures can become obstacles or where the routes will be shorter since following the road network will be redundant, e.g. in areas that are less built-up and the land-use consists of non-essential activities. Furthermore, there is a general uncertainty of which point sources will be connected to a future pipeline $CO_2$ network, which also can change the pipeline length.
In order to evaluate the output from GIS of the pipeline routes and their length, and the uncertainty of which point sources will be connected, the total pipeline length in meters is investigated with -20% and +20%. This input is changed in the economic evaluation of the pipelines, for both onshore and offshore in pipeline in order to fully understand the impact of the pipelines on the results. The impact that the pipeline length has on cost in each of the scenarios is depicted on figure 8.20 below.

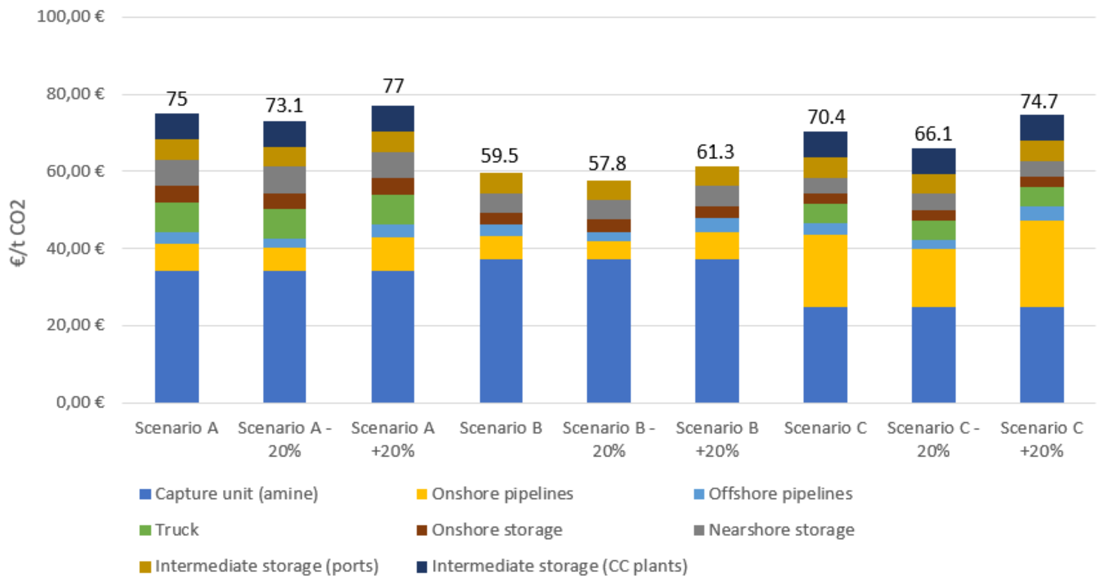


**Figure 8.20.** Sensitivity of pipeline length impacting cost/ton $CO_2$.

The cost per ton $CO_2$ depicted on the figure shows that changes in pipeline length (both onshore and offshore) has a minimal impact on the accumulative cost per ton $CO_2$. The results show that the scenarios where pipeline length is decreased with 20% are more feasible due to lowered investment costs for same amount of $CO_2$ transported. However, the increase and decrease of the cost are minor and does not show that pipeline length is decisive for the feasibility of the CCUS infrastructure.
The impact that changes in pipeline length has on the NPV and thereby whether or not the length impacts the socio-economic situation, is depicted on figure 8.21.

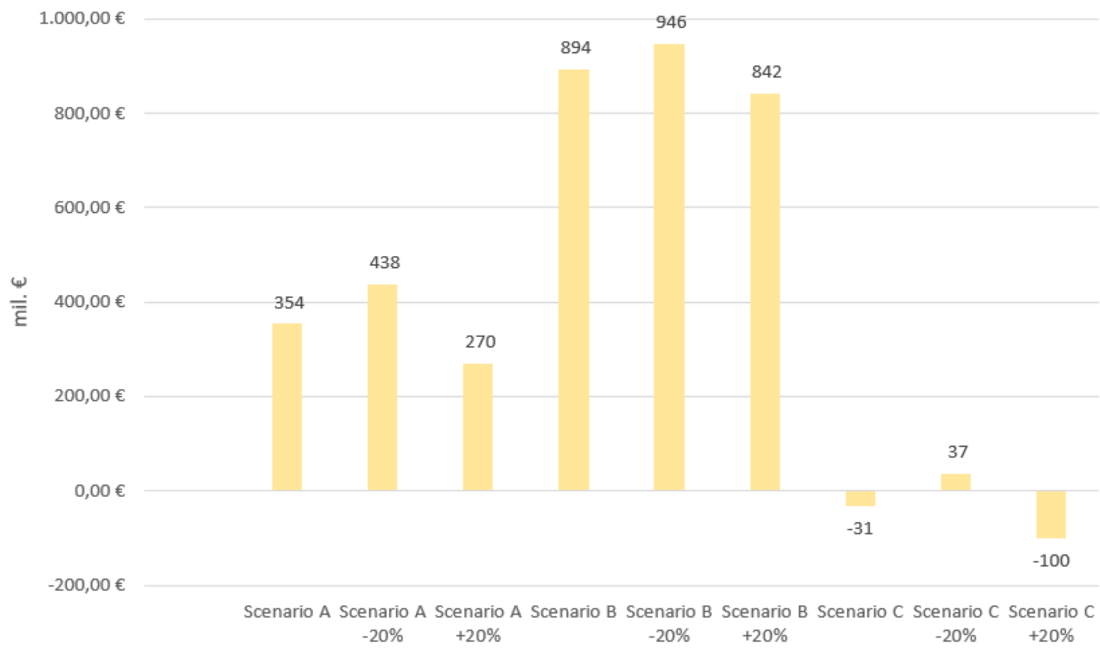


**Figure 8.21.** Sensitivity of pipeline length impacting NPV.

Again, the decrease of costs benefit the scenarios, and this is particular visible in Scenario C, where the decrease (-20%) in pipeline length leads to the scenario becoming feasible. This indicates that Scenario C would benefit from less pipeline length and alternative routes or addition of more truck transport could be considered.
The results of the NPV of which scenario is most feasible is however not impacted by the pipeline length which indicates that the overall results are not sensitive to changes in the pipeline length. Even though the routes are uncertain, the results show that the transport through pipeline will still be feasible if the pipeline length is increased.

### 8.5.2 Investment Costs

The investment costs for the technologies used in the economic evaluation of the CCUS infrastructure is based on The Danish Energy Agency [2021e] "Technology Data – Carbon capture, transport and storage". The investment costs are subject to a high degree of uncertainty which is why the report from The Danish Energy Agency [2021e] also states a high and low number for the investment costs. The range of what the investment costs can change, are for the low numbers between -10% to -25% compared to the applied cost, where the range for the high numbers are between +4% and +76% higher than the applied cost. This large range is especially influential on the investment of CC plants where there is a potential addition of 76% on the cost. This shows that the expected high and low values for other technologies might not affect the results as much as the capture plants.
The specific numbers are listed in Appendix A.10. Therefore, this uncertainty is evaluated in a high and low calculation of the investment costs to show the range observed in the economic results. The results of this change in investment cost and impact on cost/t $CO_2$ is depicted on figure 8.22.

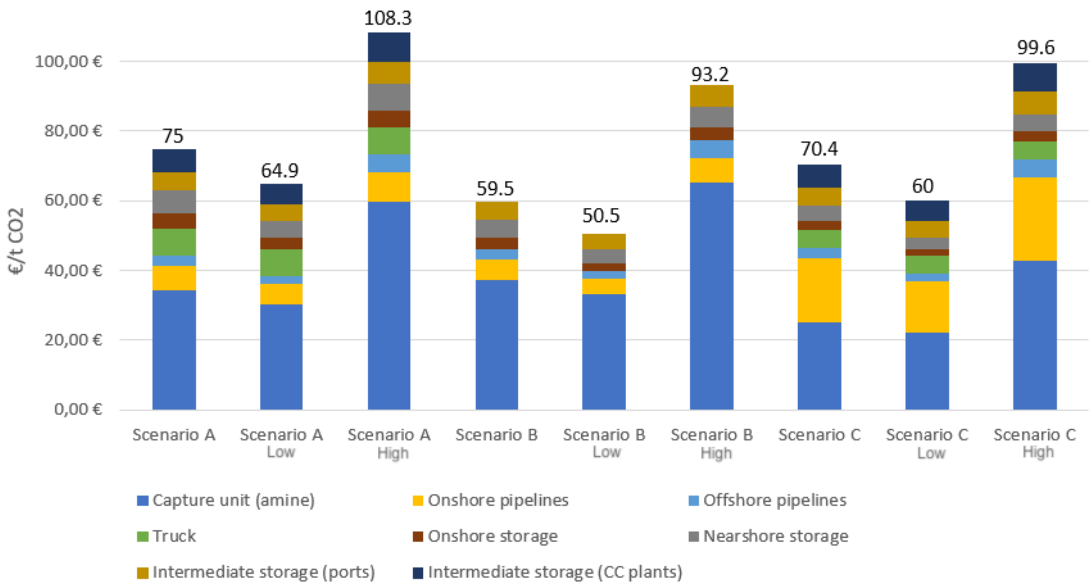


**Figure 8.22.** Sensitivity of investment costs on €/t $CO_2$.

As expected, the cost/t $CO_2$ is influenced by the high and low investment costs of the technologies. Especially the high investments costs increase the overall cost/t $CO_2$. However, this does not affect the result of the most feasible scenario as scenario B in

all cases is the scenario with lowest cost/t $CO_2$.
The investment cost impact on the NPV results are depicted on figure 8.23.

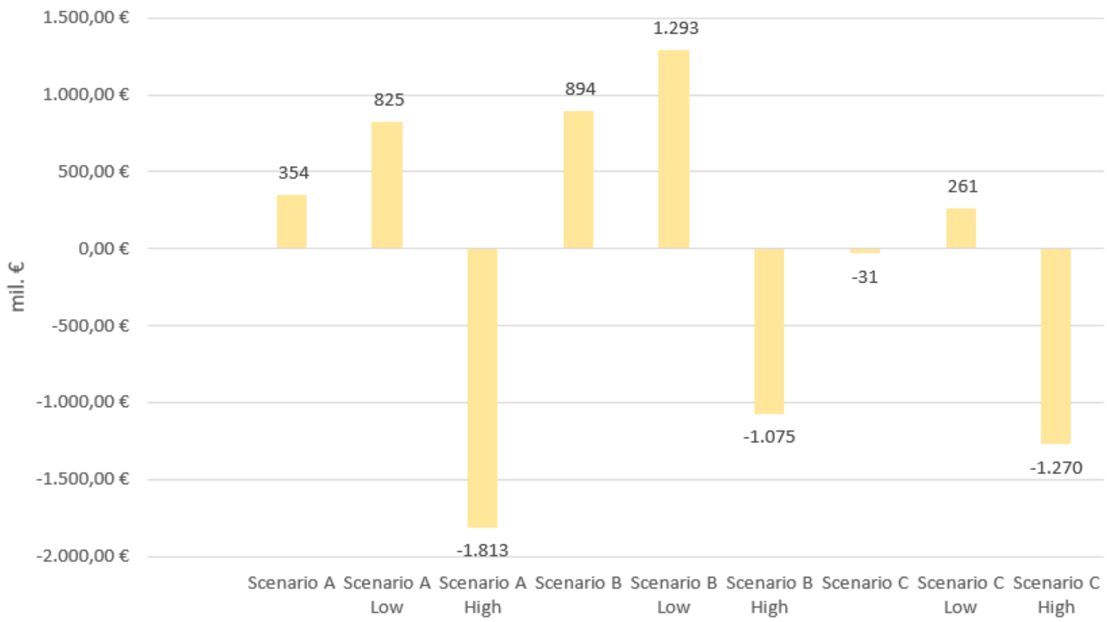


**Figure 8.23.** Sensitivity of investment costs and impact on NPV.

The change in NPV is similar to the change seen in cost/t $CO_2$ which further underlines the uncertainty of this aspect of the infrastructure. However, with the increased cost of the investment in the technologies, all scenarios have negative NPVs, which highlights the uncertainty of the investment cost as an aspect that impacts the feasibility of the CCUS infrastructure. If the high investment costs are applied, all investigated scenarios are socio-economically unfeasible. If this happens, the incentive for investing in and implementing CCUS infrastructure significantly decreases.

### 8.5.3 Discount Rate

The sensitivity of a discount rate used to calculate the annuity of the technologies' yearly costs for investment is in this analysis investigated with lower discount rates that are advised by The Danish Energy Agency [2022] for projects with longer lifetimes. This could be the case for a CCUS project, as several of the components in the scenarios have longer lifetimes than 30 years. The discount rates investigated are 1.5% and 2.5% respectively as given by The Danish Energy Agency [2022]. The original discount rate applied in the economic evaluation is 3.5%.
The impact in cost/t $CO_2$ of the changed discount rate is depicted on figure 8.24.

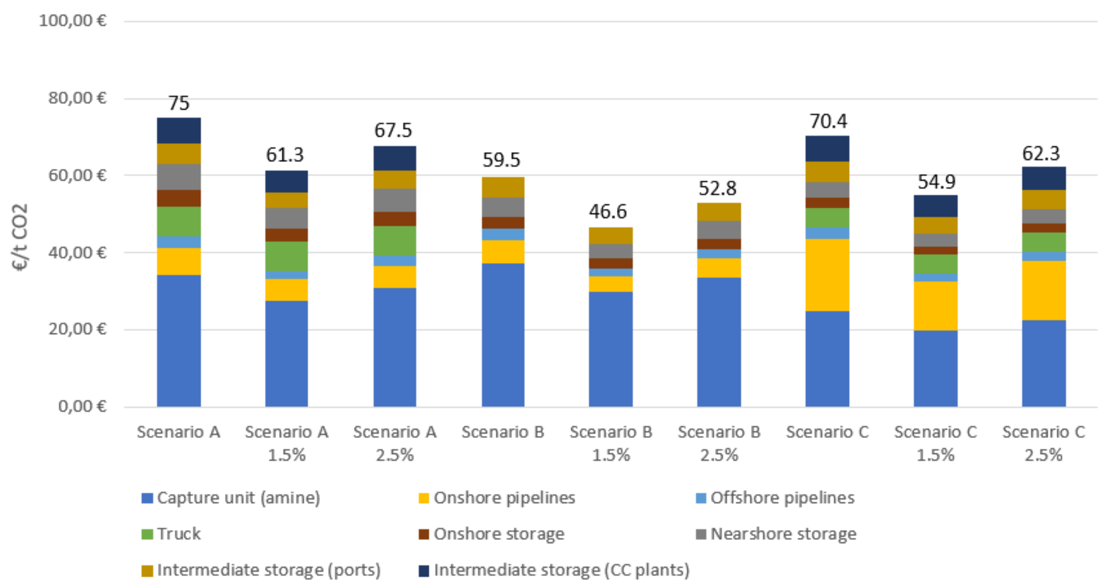


**Figure 8.24.** Sensitivity of discount rate on cost of t/$CO_2$.

The cost per t $CO_2$ is affected by the lower rate, and significantly reduces the costs. The technologies that have higher investment costs and lower O&M cost are reduced more, since the annuity calculation is used for the investment, and therefore reduces the annual cost for investment. This is for instance valid for the capture unit.

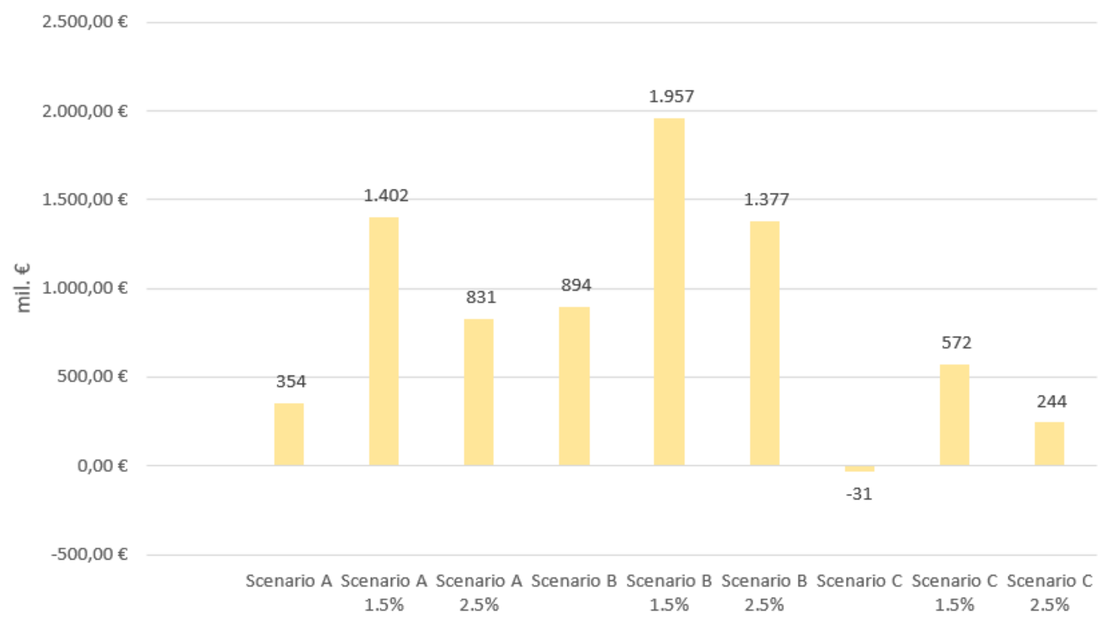


**Figure 8.25.** Sensitivity of discount rate on NPV results.

The discount rate that is used in socio-economic scenarios is advised to be 3.5 % [The Danish Energy Agency, 2022]. A higher discount rate will value future income in a scenario lower. Therefore, the lowest discount rate of 1.5% increases the feasibility of all scenarios, and also means that scenario C becomes feasible. Scenario C becomes feasible already at 2.5% indicating that the scenario is sensitive to the discount rate.

When using a lower discount rate in the annuity calculation and NPV calculation, the yearly costs will be given a higher value in the future, making the scenario more unfeasible than when using a higher discount rate. Therefore, it could be discussed which discount rate is the most applicable when evaluating a CCUS infrastructure. By deciding the discount rate, it is determined how high the cash flows from CCUS infrastructure is valued in the future – this sensitivity analysis shows, that by determining this, it can be decided if the investment is feasible beforehand. The choice of discount rate will however also depend on the general economic setting that the infrastructure in.

### 8.5.4 Price of $CO_2$ Emission Allowances

In order to include a benefit from the captured $CO_2$ from each scenario, the price of the $CO_2$ is applied as a mean of income.
The uncertainty regarding the price of $CO_2$ is determined by The Danish Energy Agency [2022], that set a low and high value to be used for sensitivity analyses. The price used in the scenario is 99.1 €/t $CO_2$ for 2030 prices, and the prices in the sensitivity analysis are 79.3 € for the low price and 204 € for the high price. Only the NPV results are shown in this regard, as the $CO_2$ price is not used in the calculation for costs per t $CO_2$. The results of changes in the $CO_2$ price is shown on figure 8.26.

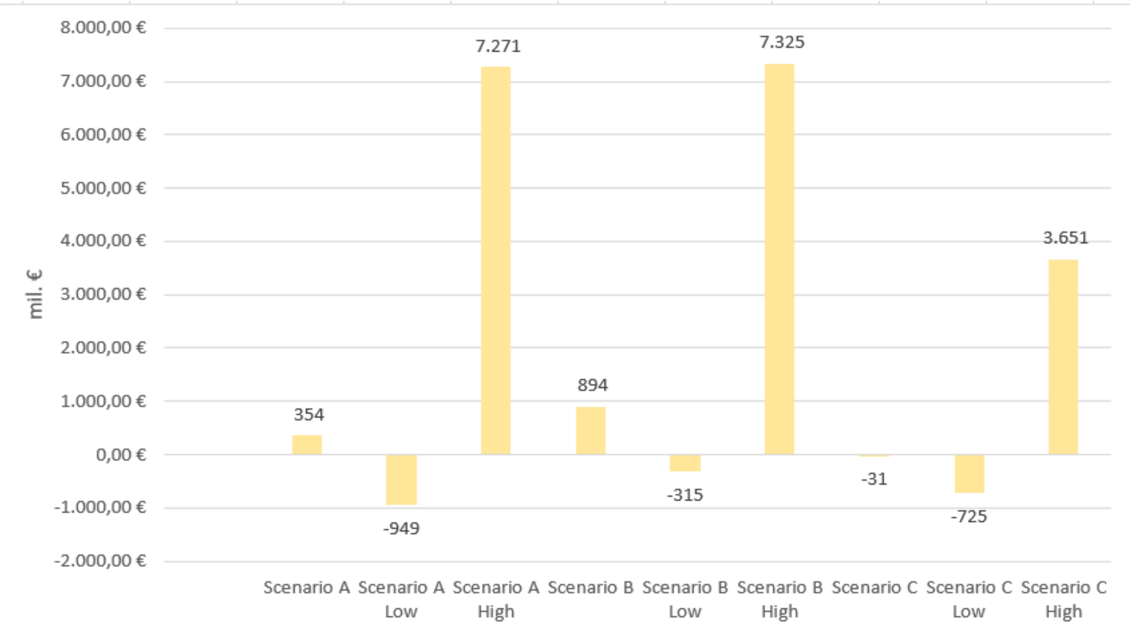


**Figure 8.26.** Sensitivity of $CO_2$ price on NPV.

It is clear from the NPV results that the $CO_2$ price have a significant impact on the feasibility of the scenarios. All scenarios have a negative NPV with the low $CO_2$ price of 79.3 €/t $CO_2$, which indicates that changes in the price of $CO_2$ can have an impact on the socio-economic benefits of the CCUS infrastructure if the $CO_2$ is not valued high enough. Furthermore, all scenarios, including scenario C, are feasible with the high $CO_2$ price of 204 €/t $CO_2$. Scenario A and B are also close in NPV value indicating that the higher amount of $CO_2$ that is captured in Scenario A benefits the socio-economic results.

## 8.6 Partial Conclusion

The spatial arrangements of the scenarios provided the input for the economic analysis and shows that the three scenarios are similar to a broad extent. The varying point source emission capacities however impact the costs and feasibility of the scenarios and shows that scenario B is most feasible and scenario C is not feasible in a socio-economic sense due to a negative NPV. The sensitivity analysis on the economic parameters has shown that most uncertainties do not affect the results of the NPV calculation and the calculation of cost/t $CO_2$. This is partly due to the high similarity of the scenarios in terms of technology selection. The most distinctive effect on the NPV results is seen when the price of $CO_2$ emission allowances is increased, which leads to a positive NPV and thereby a feasible investment for all scenarios. Furthermore, lowering investment costs for all technologies benefit scenario C as well as lowering the discount rate, indicating that the future perspective that scenario C induces can become a valid solution for the CCUS infrastructure.

# 9 Implementation of CCUS Technology

The final chapter of this report's analysis contains an investigation of how a CCUS infrastructure can be implemented. Implementation is in this case defined as a process in which planning and execution of CCUS infrastructure takes place. This entails initial analyses and examinations to the initiation of concrete plans and finally when the technology is constructed and in operation. The findings in this chapter is predominantly based on findings in interviews with actors involved with CCUS infrastructure in different ways – the goal of these are to learn the expectations from different actors to a CCUS infrastructure, and to find the greatest challenges and how these can be mitigated in the implementation process. The results of the previous analyses are held against these findings when relevant.
The actors that have been interviewed and how their role fit with CCUS value chain is depicted on figure 9.1.

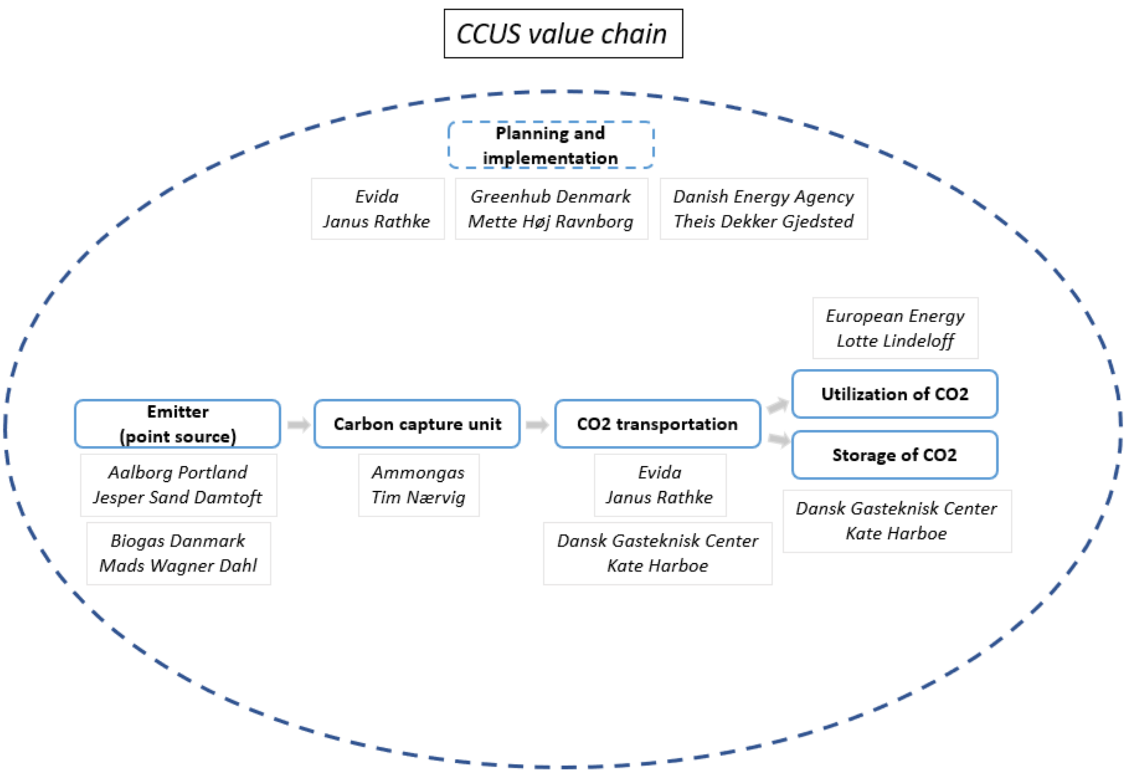


**Figure 9.1.** The roles of interviewees according to the CCUS value chain.

The content of the analysis is split into five parts – Technique, Product, Profit, Organization, and Knowledge – as guided by the technology definition described in section 6.1. This is done to ensure that all topics within the technology is covered and presented. In the final part of the chapter, a partial conclusion sums up the main points of the analysis and relates these to the technology definition and choice awareness theory.

## 9.1 Technique

The first topic of *technique* revolves around how the physical CCUS infrastructure should be configured, ie. how $CO_2$ should be transported and stored or utilized, and furthermore, which challenges and uncertainties that are connected to this. Across the interviewees, most agreed that pipeline infrastructure make sense for the most part, and that trucks can be used for smaller quantities. Lindeloff [2023] mentions that the interconnected infrastructure only makes sense, if it is cheaper than transporting it individually – this then depends on the design of the infrastructure.

Several actors, such as Dahl [2023]; Harboe [2023]; Gjedsted [2023]; Ravnborg [2023] indicate that the mode of transportation depends on the quantity that is transported – Damtoft [2023] specifies that a boundary that could be used for this distinction could be that emitters of less than 50,000 t $CO_2$/year could be using trucks and larger than that would be connected to a pipeline. This can be related to the results of scenario B where point sources above 40,000 t $CO_2$ result in a CCUS infrastructure arrangement of pipelines exclusively and therefore represents another threshold for point sources. The difference between 40,000 t $CO_2$ and 50,000 t $CO_2$ is minor, however, it would result in 6 out of 11 point sources being excluded from the network. This would reduce the $CO_2$ quantity sent through the pipelines in the scenario which potentially would decrease the feasibility.
Rathke [2023] specifies that a pipeline network could be set up with a transmission line that accumulates large amounts of $CO_2$, so that emitters will be connected via smaller pipelines to this. Furthermore, Damtoft [2023] adds to this that pipeline should be designed to a national scale and also be able to accommodate a connection internationally to ie. Sweden and Germany – in the EU, CCUS projects and infrastructure projects are of interest, where the focus is to establish a trans-border European $CO_2$-infrastructure [European Commission, 2021a]. In this report, the scope is only concerning Northern Jutland – meaning that the idea of a national or international infrastructure goes beyond the spatial and economic evaluation. If the analysis was done on a national level, this would increase the complexity of a CCUS infrastructure, as more point sources, sinks, and routes would be analyzed.
In Northern Jutland, a new project of $CO_2$ import at the Port of Aalborg has been announced with commission in 2026, where the private actor Fidelis New Energy together with the Port of Aalborg are behind the project [Port of Aalborg, 2023]. However, there are currently no official plans of a specific infrastructure for this. The only other plans are the analyses and ideas for CCUS infrastructure in Northern Jutland by Green Hub Denmark [2022].

The challenges that are mentioned in regards to the physical transportation of $CO_2$ can be divided into three topics. Firstly, the pressure within pipes should be configured. The

pipes can transport the $CO_2$ in a gaseous state, ie. with a low pressure in the pipes, or as a liquid, where the pressure is higher. The assumption of the previous analysis is a high pressure $CO_2$ pipeline network, and this indicates that the costs might be lowered if low pressure is applied in some parts of the network, which could benefit the overall economic results. This is, according to Rathke [2023] a weigh-off between the high costs that are included in liquefaction of $CO_2$ in order to condense it to liquid, and the larger pipes that are needed when transporting with a low pressure, since this takes up more space and therefore adds to investment cost.
Secondly, the switch between different modes of transportation must be coordinated. This is mentioned by Dahl [2023] and goes in line with the previous challenge of the pressure in the pipes. If both trucks, and low- and high pressure pipes are used, the need for interconnecting stations will be higher and thus more intermediate storage and liquefaction plants will be needed – which in turn could increase the costs of the network.
Thirdly, a common concern is how the dimensions of the system will be planned for. Ravnborg [2023] mentions that much of the infrastructure depends on whether $CO_2$ will be imported or exported and how large the quantities of this will be. Harboe [2023] mentions that there should be carefulness around dimensioning pipes, so that they are not overdimensioned for the future use. The dimensions are also commented on by Gjedsted [2023], that highlights the uncertainty in not knowing which emitters will be connected to a common pipeline and when this will happen, as this could affect the scale that is needed. This is also a general concern that has been investigated in the spatial analysis where different sizes of point sources are analyzed. The analysis showed that the complexity of the infrastructure differentiates with the amount of point sources connected.

### Main Points

The essential points of the infrastructure's technique are as follows;

- Mode of transportation depends on quantity of $CO_2$.
- It must be determined in which state the $CO_2$ should be transported.
- There is a high uncertainty in dimensioning pipelines for current and future use which relates to the uncertainty of which point sources will be connected in the future.

## 9.2 Product

In line with technique, *product* is regarding the final infrastructure and set-up of how the $CO_2$ will be utilized. This correlates with the previous section, and the challenges that are described, such as the dimensioning of pipelines that are a part of the general CCUS infrastructure, ie. the product.

The common input about the final $CO_2$ infrastructure across the interviewees is that no one has a clear vision of how the infrastructure should look. As mentioned previously, it is suggested that an infrastructure consists of both pipeline and truck transport. Highlighted by Harboe [2023]; Rathke [2023]; Damtoft [2023], the pipelines could consist of one or more transmission lines, that emitters can connect to. The emitters can either be connected via pipes or trucks, according to what makes sense economically. The spatial analysis configured a network that does not have this sense of transmission line, but where all of the point sources and sinks are connected in one large network. Therefore the results differ from what is otherwise expected from actors in the CCUS infrastructure.

When looking at a time perspective, several actors are also specifying that on a short term basis, trucks would probably be used as the only mode of transportation. An advantage to using trucks according to Dahl [2023], is that the trucks can be more economically feasible for smaller biogas plants, and furthermore, that they are flexible when it comes to routes and distances between the emitters and sinks. In the scenarios of this report, the trucks do not have a significant size in the cost/t $CO_2$ – however, this is due to the fact that the trucks are only used for shorter distances, and not used at all in scenario B. A more detailed economic evaluation where trucks are used in the first years with fewer emitters, would highlight the feasibility of this proposed configuration.

In Norway, a CCS project named Longship is used as a demonstration project where industries and other countries can gain inspiration and knowledge from [Gassnova, 2023]. Several interviewees mention this project as something that will have an impact on the way the Danish infrastructure will be designed and how $CO_2$ is stored, because the project can be used as a source of inspiration. There are however some differences if the Norwegian project is compared to the situation in Northern Jutland, as the project in Norway only concerns CCS and transportation to storage site is mostly via ship [Gassnova, 2023].

The final product of the CCUS infrastructure is not only the transport of $CO_2$, but also the capture and end use of it. Gjedsted [2023] and Dahl [2023] express that carbon capture should be focused on certain emitters that can not be electrified – Dahl [2023] further mentions that biogas plants already have the capture plants if they wish to send upgraded biogas on the natural gas network and are therefore "low hanging fruits" where it makes sense to start the development. Gjedsted [2023] says that the point sources should be filtered in order to avoid "carbon lock-in". To add to this he says:

> *"In Denmark this is not such a big issue [...] Politically, it is said that it [CC] should not be on coal-fired power plants, and they are almost phased out. Then we have these "hard to abate" sectors where most agree that CC should be placed, such as cement and waste."*

When discussing the end use of $CO_2$, the time perspective is again a factor that influence the interviewees' response. Currently CCS has the shortest time perspective in regards to when it will be ready to use in Denmark. The offshore CCS project Greensand was initiated in 2023 and in May 2023, Ørsted signed a contract for funds for CCS from two locations, where the $CO_2$ is transported to an offshore storage site [Project Greensand, n.d.; The Danish Energy Agency, 2023c]. Both Gjedsted [2023] and Rathke [2023] emphasize that a CCUS infrastructure should focus on storage in the beginning, and when the technology and market is mature, it can be accommodated to be used for utilization in PtX facilities as well. Another benefit from storing $CO_2$, is the fact that the biogenic $CO_2$ that is stored permanently will be counted as negative emissions which has a more positive effect on the climate account compared to when it is reused for e-fuels and still emitted to the atmosphere [Damtoft, 2023]. The Danish Ministry of Climate, Energy, and Utilities has a fund for Carbon Capture, Storage and Utilization of $CO_2$ that is focused on CC of flue gas from point sources, and a fund for Negative Emissions (NECCS), that is focused on CC of biogenic $CO_2$ from point sources without combustion, e.g. biogas upgrading [The Danish Ministry of Climate, Energy and Utilities, 2021d]. Firstly, the funds focus on storage of $CO_2$, but are also ready to accommodate the need for utilization of both the fossil and biogenic sources in the future [The Danish Ministry of Climate, Energy and Utilities, 2021d]. The previous analysis takes point of departure in year 2030, and assumes that both storage and utilization will exist.

In line with the distinction between focusing on storing or utilizing $CO_2$, the distinction between fossil and biogenic $CO_2$ comes along. Most interviewees agree that the distinction between the two are important. Damtoft [2023]; Harboe [2023]; Gjedsted [2023] all agree that it should be prioritized that fossil $CO_2$ is stored permanently. Lindeloff [2023] and Damtoft [2023] underline that the distinction of biogenic and fossil $CO_2$ is important when using it for production of e-fuels via PtX. This is because the producer of e-fuels must be able to prove that the $CO_2$ used is sustainable, for the fuels to be labeled as sustainable. Rathke [2023]; Ravnborg [2023]; Damtoft [2023] agree that in order to guarantee this, a certificate system could be used to ensure the amount of biogenic $CO_2$ in e-fuel production. In this way, $CO_2$ from sources with mixed biogenic and fossil $CO_2$, can also be used for e-fuel production, if certificates from biogenic $CO_2$ is secured. According to Damtoft [2023], these certificates could resemble the existing biogas certificate system, where Energinet keeps track of how much biogas that is added to the gas distribution in Denmark, and issues certificates for this amount [Energinet, n.d.b].

### Main Points

Based on this description of the final product of a CCUS infrastructure, the main points can be condensed as;

- Transport of CCUS can consist of both truck and pipeline transport, but trucks will be used initially.
- Both storage and utilization of $CO_2$ is relevant, but storage is initiated first.
- $CO_2$ should be divided in fossil and biogenic via a certificate system.

## 9.3 Profit

The *profit* element of the technology definition is relevant in terms of the CCUS infrastructure and its implementation. Investigating profit streams and other elements related to this, aids in understanding ownership of CCUS infrastructure elements and the interests of this.
The CCUS infrastructure differs from other energy technologies since its development to a large extent relies on the involvement of private actors but is based on initiatives taken from public actors. The CCUS infrastructure can however also be constructed based on the willingness from private actors, which is where $CO_2$ differs from other gasses from e.g. natural gas, where there are a few large sources with transport that is operated by the public sector.
Among the interviewees there is general consensus of who should own a pipeline-based $CO_2$

network in Northern Jutland, which is Evida, the state owned gas distributor. Evida is already involved with several $CO_2$ projects and has also been given the ability to distribute $CO_2$ within their line of work [Evida, 2023]. According to Dahl [2023], it would make sense for Evida to be the owners of a such pipeline system where the public authorities will set a tax and tariff level and the market will set a price of $CO_2$, which then will make the price of transporting the $CO_2$ in the network. Lindeloff [2023] argues that it is important that this price reflects the actual use of a potential pipeline system, and does not make it more expensive than necessary. Furthermore, the $CO_2$ infrastructure setup can be inspired by the current natural gas setup [Harboe, 2023].
Rathke [2023] says that:

> *"It will probably be us who should do it [...] there are some local areas where they [the market] want to start laying pipes. We are open for that, and can find a solution for that, since they cannot wait for us to develop all of this, we cannot start all over. Maybe we can help with the operation later on, but there are many ways to cooperate. We are probably to facilitate since we have the communication with the different aspects, such as the Energy Agency"*

– which further marks Evidas possible role in this connection.
The possibility of Evida being the facilitator of the investment is also mentioned as an option by Gjedsted [2023] who also mentions that the possibility of the infrastructure being owned by private actors is possible – and that there legally is no hindrance of either option. The Subsoil Act opens up for private actors to store $CO_2$ in the underground [The Danish Ministry of Climate, Energy and Utilities, 2019]. Lindeloff [2023] further underlines that private owning could have a positive impact on the profitability of connecting to a CCUS infrastructure, since the infrastructure would be developed on a market basis and therefore reflect the market cost, however, there is a vulnerability in the fact that private companies would be the owner of critical infrastructure – this could ie. be in terms of security of supply. Harboe [2023] also states that the market will impact the competition which will have a potential positive impact on the implementation of the infrastructure.
A concern amongst most of the interviewees is that many actors are waiting for the correct financial support or subsidy schemes initiated by the government, and as Ravnborg [2023] states:

> *"People are waiting for some framework conditions, some statements or guidelines, from the state or some Ministry stating "this is the way to go". For some, this wait might be frustrating, since it is difficult to navigate in something you don't know what is, which also relates to how this infrastructure should be built"*

This is discounted by Nærvig [2023] who believes that the market can overcome potential setbacks brought by missing regulation and subsidy schemes. Damtoft [2023] and others mention the Longship project in Norway [Gassnova, 2023], where the Norwegian state and the industry partners share risks and costs, but there is a potential subsidy support of up to 100% of the CAPEX and OPEX from the government [Agrocura, 2023a]. Having this relationship between the state and market aids to reduce uncertainties to a large

extent and thus provides a foundation for CCUS development, which could inspire a such relationship in Denmark as well.
Generally, the interviewees agree on the emitter being the one paying for the capture units. Damtoft [2023] argues that it is necessary for a company like Aalborg Portland to receive some kind of subsidy or support scheme in order to make these large investments, since the investment will not be earned back in the current subsidy environment. Currently, Aalborg Portland pays a lower tax on $CO_2$ than other emitters – Damtoft [2023] argues that if this $CO_2$ tax is increased, then the carbon capture business case for Aalborg Portland would not be feasible. Another point made by Lindeloff [2023] is that the PtX developer can be part of investing in a capture unit since this potentially can improve the business case for the PtX project. This opens up the discussion of how the large investments are divided across the CCUS value chain. An outline of the suggested ownership distribution across the value chain are illustrated in figure 9.2.

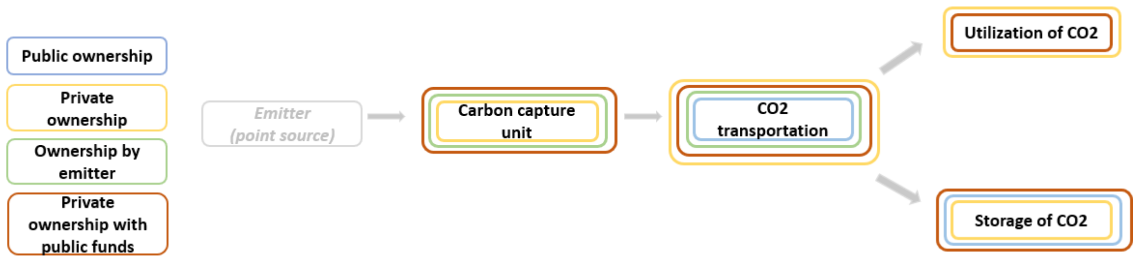


**Figure 9.2.** Different ownership options for each components of the CCUS infrastructure.

As mentioned, most actors point to Evida as the facilitator of the investment, and that the investment should be funded by the state. Lindeloff [2023] however mentions that depending on the cost for connecting to the public infrastructure, private investments can also be made in transporting $CO_2$, if that is more economically feasible.

There are several uncertainties that can affect the size of the investments across the different components of the infrastructure, such as the quality of the $CO_2$, where the PtX developer are not willing to take the risks of investing in purifying units before injection in the pipes if the general quality in the pipes are lower. Instead, a purifying unit at the PtX plant would be necessary [Lindeloff, 2023].
The question of who is to invest in what part of the CCUS value chain is something that is not part of the economic evaluation in the previous analyses. In the CCS strategy from the Danish state it is clear that the state wants a market based penetration of CCS that firstly is supported by financial pools, but will later be supported via taxes and expenses for $CO_2$ emission allowances [Socialdemokratiet et al., 2021]. This somewhat supports a joint effort between private and public actors to develop a CCUS infrastructure.
A subject that Dahl [2023] and Gjedsted [2023] brought up is Climate Credits [SEGES Innovation, 2022]. Here, Gjedsted [2023] states that there is an increased interest from the market in these credits as part of paying for the CCUS. The climate credits are more widespread in the agriculture sector where climate initiatives save $CO_2$ which then can be bought by others through the climate credits [Agrocura, 2023b]. In the connection with CCUS, the climate credits could aid companies with reduction of emissions if CCUS falls

under an applicable category on the climate credits. An example of these credits are in the project that Ørsted has won the state's funding for. The project is furthermore supported by Microsoft who will buy the $CO_2$ emission reduction from the project over a period of at least 11 years – Ørsted furthermore states that the combination of the state's tender and the funding from Microsoft both has been necessary in order to realize the project [The Danish Energy Agency, 2023c]. This means that the financial pool is not necessarily enough to ensure the business case for the project, but the involvement of other investors is vital.

### Main Points

The subject of profit covers a wide range of factors that impact the implementation of CCUS infrastructure in Northern Jutland. The main aspects that have significance on the profit streams and ownership of the CCUS infrastructure are:

- Ownership of the $CO_2$ pipe network should be public but a positive attitude towards private involvement is observed.
- The market players could enter into the CCUS value chain and play a larger role as competition would aid a faster and perhaps more realistic costly infrastructure. However, an infrastructure benefits from collaboration between both public and private actors.
- There is hesitation in the market towards initiating any steps towards CCUS implementation due to lack of fulfilling support schemes.

## 9.4 Organization

The *organization* of the CCUS infrastructure relates to how the CCUS infrastructure is planned for and how the infrastructure's organizational framework is set up. This is for instance how the relevant legislation and regulation impacts the development of CCUS infrastructure. Furthermore, this aspect describes who the initiators of the development of CCUS infrastructure could be and which initiatives are to kickstart such a development. The capital to kickstart the development of such an infrastructure should according to Dahl [2023]; Damtoft [2023]; Ravnborg [2023] come from the Danish state. This is to ensure that it becomes attractive for companies to participate in the CCUS infrastructure. Additionally, according to Damtoft [2023], the market is not able to initiate such a task because the investments are too substantial to make when there is a high uncertainty in the market for CCUS. Furthermore, Harboe [2023]; Dahl [2023]; Rathke [2023]; Damtoft [2023] also agree that the Danish State and the government should be the initiators of steps towards a CCUS infrastructure, and especially if any pipelines are to be constructed. However, there might be a point where the market cannot wait any longer or will be financially strong enough to participate in the planning.

Rathke [2023] argues that the DEA have a large impact on the development with the financial support pools that are currently on tender [The Danish Energy Agency, 2023c; The Danish Ministry of Climate, Energy and Utilities, n.d.], and continues with

> *"It is a good idea to start with the funds from the CCUS tender, where they need to start with the capital themselves but DEA is willing to chip in, so it gives some security and learning"*

which supports the general opinion of the role the market is to play and the general collaboration and interaction between the market players and the Danish state. Also the EU should be part of the initiating actors according to Lindeloff [2023] and Ravnborg [2023], since EU funds might be applicable and because of the possibility of the CCUS infrastructure crossing country borders either in the form of $CO_2$ or via e-fuels.
The role of the state is further mentioned by Gjedsted [2023] who raises the question of whether an overall guiding and coordinating political direction is the way to go or if the market is ready to deal with this itself. This missing aspect of a general guide is supported by Ravnborg [2023], who underlines the fact that it is difficult to plan and act in a setting that is currently evolving and therefore a more fixed guideline would be helpful. A clear regulatory framework and guidelines is also a point in the CCS strategy, but has nevertheless not been followed up yet or communicated clearly to the involved actors in CCUS [Socialdemokratiet et al., 2021].
As part of the general regulatory setting that the implementation of the CCUS infrastructure moves in is the price of $CO_2$. Both Damtoft [2023] and Gjedsted [2023] argues that current levels of the $CO_2$ prices are insufficient to make sure that there is a business case in CCUS for the emitters. Damtoft [2023] says that in relation to cement production:

> *"The development of CO2 costs and prices means that there will come an additional cost in the long run [...] if you get a uniform CO2 tax in Europe, that would be an incentive to invest and reduce emissions"*

This additionally highlights this area of the legislation as a very complex factor that can have decisive influence of the capture aspect of the CCUS infrastructure.
The price of $CO_2$ should be able to stimulate several markets within the CCUS value chain, however, it is still a challenge to get the whole value chain up and running to make sure that all parts of this is ready for the implementation [Gjedsted, 2023]. Rathke [2023] highlights that the willingness to make actual deals is lacking, which perhaps is the hesitation due to uncertainties of market formation and upcoming legislation.
An important aspect for the spatial and actual implementation of a $CO_2$ network is the option of expropriating land for the routes of the $CO_2$ pipeline [Rathke, 2023], which currently is not something that Evida has the legal basis for. All of the interviewees agree that pipeline transport of the $CO_2$ will be essential for some parts of the CCUS infrastructure, and therefore, not having this option will delay the process due to a more intense authority processing. Whereas the option of expropriation will mitigate time obstacles to a large extent [Energinet, n.d.a].

According to the statements from the interviewees, a range of regulative instruments are missing for ensuring a successful implementation of CCUS infrastructure in Denmark. As stated by Lindeloff [2023] this is for instance certificates for sourcing the $CO_2$. This is related to controlling the origin of the $CO_2$ when it is used in e-fuel production, and to document that the e-fuels produced are renewable. The e-fuel production has to measure up to EU regulation such as the RED II directive, which is decisive for whether or not the e-fuel can be marked as sustainable [European Commission, 2021b]. Therefore, certificates for origin of biogenic $CO_2$ is important for PtX developers to ensure RED II compliance.
An initiative that would aid the implementation according to Lindeloff [2023] is a more subtle "nudging" of the market, where incentives are brought by the government in such a way where e.g. market players are encouraged to store or utilize $CO_2$ since this would be the only alternative. Damtoft [2023] agrees with this and refers to the setup in Norway, as explained in the previous section. This nudging or market incentives could also be inspired by the Inflation Reduction Act (IRA) in the US that to a large extent aids the market to where the production of e-fuels are on the level of the cost of fossil fuels [The White House, 2022].
Another regulatory element of the CCUS infrastructure relates to ownership, where Rathke [2023] highlights that the regulation relating to this is not fulfilling, since some ambiguity of if there should be private or public ownership is not dealt with in current legislation. Furthermore, a question of the ownership in the pipelines is raised by Damtoft [2023], since there are uncertainties of when the ownership of the $CO_2$ in pipelines switch from the emitter to the transport operator and/or the storage owner or utilization user. Damtoft [2023] here highlights that in the first round of the tender sent out by the Danish Government, the emitter has responsibility of the $CO_2$ until it is stored.
Harboe [2023]; Gjedsted [2023]; Ravnborg [2023] highlights that a general framework of safety and standards for $CO_2$ transport is missing. This relates to the fact that CCUS is a new subject in a Danish context. The work relating to $CO_2$ standards has already been initiated by Danish Standard [Dansk Standard, 2022], and this is very important as the purity of the $CO_2$ to be transported in pipelines will impact the business case of capture plants as well as the utilization of $CO_2$. All these uncertainties are part of creating hesitation in the CCUS value chain, since actors do not wish to make investments that later would prove to be unnecessary, such as liquefaction plants at the capture plants [Dahl, 2023].
Generally, Lindeloff [2023] and Ravnborg [2023] problematize that the overall clarity of the legislation for implementation is to be expected from the state. A more holistic view around the planning of such infrastructure would aid the implementation since now there is very little or none legislation directed towards CCUS infrastructure implementation. This is supported by Ravnborg [2023] who argues:

> *"Something that the actors are missing are some specific guidelines [...] it would help many actors if there would come a legislation on the area, so you can get a proper start. There are many who do not dare to start before they know the conditions or framework"*

Therefore, this further underlines that the regulatory environment for CCUS infrastructure in Denmark is currently not working for a successful implementation.

One initiative from the Danish State is the financial pool tender for large scale CCS projects in Denmark [The Danish Ministry of Climate, Energy and Utilities, n.d.]. The interviewees are divided on the subject of whether this incentive is aiding the implementation of CCS in Denmark. Rathke [2023]; Gjedsted [2023] and Harboe [2023] highlights this initiative in their interpretation of the current regulatory environment as supporting a positive development. On the contrary Nærvig [2023]; Dahl [2023] and Damtoft [2023] states that these support schemes should be targeted more directly to support the actors in initiating CCUS projects. This could ie. be by lowering the risks of investment by spreading the financial responsibility and stimulating all parts of the value chain [Damtoft, 2023].

### Main Points

The subject of organization covers a wide range of factors that impact the implementation of CCUS infrastructure in Northern Jutland. The main aspects that have significance on the organizational level of this are:

- Initiatives towards a CCUS infrastructure should be taken by the Danish state
- Clear guidelines in the current legislation are missing and would benefit from a holistic view on the CCUS planning
- Discrepancy of whether the current support schemes are working for a successful implementation
- Uncertainties of safety, standards and upcoming regulation on both national and EU level are creating unnecessary hesitation in the market

## 9.5 Knowledge

The final concept of *knowledge* is a broad subject, that in this case is defined as where there are gaps in knowledge, for the implementation of a CCUS infrastructure to be initiated. Therefore, the topics within this concept can also overlap with the other concepts of the chapter.

Regulation and legislation is a topic that is a reoccurring theme. Several interviewees express the wish for legislation or regulation on both sale of $CO_2$, transport of $CO_2$, and competition. According to Dahl [2023] a knowledge gap is revolving around the organization of how $CO_2$ is sold – here some legislation could regulate how this is done and favor that the $CO_2$ is used for production of e-fuels. For Lindeloff [2023], the price of $CO_2$ has a large impact on their projects' business case. The price of selling $CO_2$ to PtX projects should be able to compete with storage, so that one is not favoured. Gjedsted [2023], who works in the political area of CCUS, states that it should be identified whether there is a knowledge gap within the legislation for transportation of $CO_2$. Furthermore, there could be a need for rules regarding the competition in the area, but also for regulation of the environmental aspect, as well as safety within transport of $CO_2$ [Gjedsted, 2023].

Similar to the regulation is the topic of standardization within the $CO_2$ market and infrastructure. Both Harboe [2023]; Gjedsted [2023]; Rathke [2023] and Damtoft [2023] mention this as an important knowledge gap hindering of the CCUS infrastructure implementation. The overall need for standards is regarding the purity of $CO_2$, but this depends on different sections of the infrastructure. When the carbon is captured and the $CO_2$ initially is purified, it must be known what the purity requirements of the offtaker is – which can be a storage or a PtX facility. Then, if the transportation of $CO_2$ goes through pipelines, the purity requirements of the pipes must be known. If different purities of $CO_2$ are transported in pipes, there is a risk that the $CO_2$ again must be purified when it is extracted from pipes at the end user. In relation to this, Nærvig [2023] mentions that in their initial projects, they will be using a precautionary principle and purify the $CO_2$ as much as possible, to ensure that the product can be used even if the purity requirements at the end user are lower. According to Rathke [2023], it is important to determine what level of purity is acceptable without raising costs unnecessarily for CC plants of offtakers, which the aforementioned could be an example of. Inspiration could be gathered from existing projects, such as the Northern Lights project in Norway [Gjedsted, 2023]. Northern Lights is the part of the Longship project that is in control of transporting and storing the $CO_2$ from the two capture projects [Gassnova, 2023].

An overall topic that is mentioned by several actors can resemble that an overall plan is missing for this development. Ravnborg [2023] states that within this development, there are many actors that are willing to take action, and many have both different knowledge and opinions which makes it hard to take specific decisions. Gjedsted [2023] and Dahl [2023] agree that it is unclear from which end the development should be initiated from – whether the market should establish itself and then the infrastructure and the state's role should be accommodated to this, or, if the development should be initiated via the state or political influence. An example of the latter is the funds that the Danish government has issued to Ørsted as was described previously. This resembles a top-down approach to planning, where the state is in charge of initiating the implementation and initiate actions that engage the involved actors. Harboe [2023] follows up on this argument with a concern about the time perspective for the implementation. She says:

> *"There is a trade off of whether we [CCUS actors] should begin the development, which might make it more expensive than what is necessary or otherwise we should wait to see what the happens with the system"*

A general comment that also is in line with the discussion of who should initiate the development, is that the bigger picture is missing. Nærvig [2023] expresses this as a misalignment between what is found in technical analyses and what is actually possible to accomplish currently, which Ravnborg [2023] adds to by stating:

> *"There is a lot of knowledge out there, but the point is to make a decision based on this background. That is the challenge [...] We are building a lot of knowledge through CO2Vision. We are doing a roadmap and we have test sites that both contribute to the knowledge-bank of what is going to happen and which way to go [...] So the challenge is to make a decision on the background of what knowledge there is"*

Lindeloff [2023] and Gjedsted [2023] mention that the unpredictability of where a prospective pipeline will be located is a knowledge gap, and Lindeloff [2023] adds that this brings a large uncertainty in where PtX facilities should be placed, and that an overall plan for this could ease their planning process.

### Main Points

Summarizing this display of knowledge elements that are needed, the most important knowledge gaps within the implementation of a CCUS infrastructure are listed here:

- Regulation is needed to determine price of $CO_2$ and how the sale of $CO_2$ is organized.
- Knowledge of required $CO_2$ purity is needed to determine investment costs and to function as a baseline for standards.
- An overall plan will fill in knowledge gaps for several actors in the value chain and guide the implementation of a CCUS infrastructure.

## 9.6 Partial Conclusion

The implementation of a CCUS infrastructure in Northern Jutland is constituted by the five elements of *Technique, Product, Profit, Organization* & *Knowledge*. These elements are all interconnected in different ways and prove that change in one element will impact another. This is for instance seen with the element of product where the pipeline transport of $CO_2$ is impacted by the guidelines and framework conditions presented in the organization element.

An overall subject of the implementation process for CCUS infrastructure is the uncertainty that influence all of the elements. This high level of uncertainty means that choice awareness should be raised in the case of CCUS in Northern Jutland. It is important to investigate and analyze the planning and implementation process and to showcase the different paths towards a CCUS infrastructure.

The interconnection between the technology definition elements and the main aspects of implementation of the CCUS infrastructure are depicted on figure 9.3.

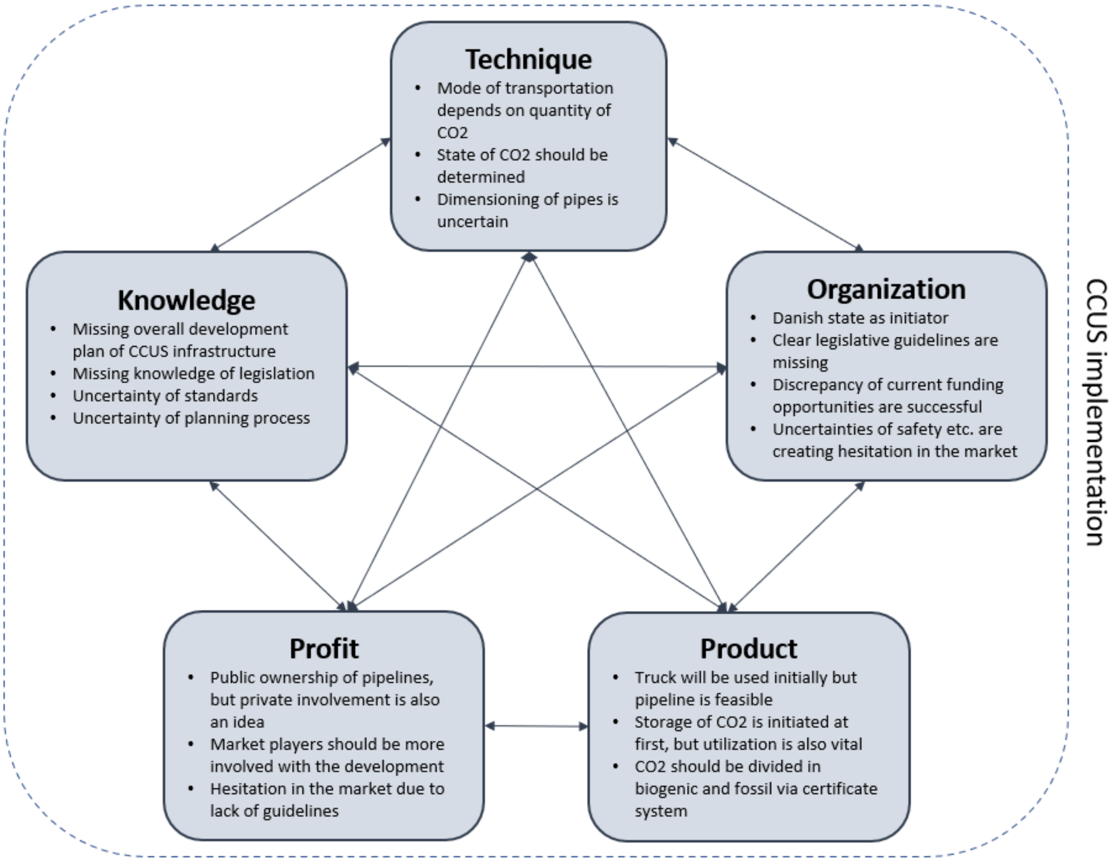


**Figure 9.3.** Aspects of implementation divided into technology definition elements.

When relating the elements and descriptions in the figure to choice awareness and radical technological change that was described in section 6.1, it is evident that changes will occur within most of these elements and thus a radical technological change is instigated when implementing a CCUS infrastructure. What is highlighted through this analysis is that the organizational aspect has a large impact on how the technique is implemented and how the final product will look. Furthermore, a large part of the knowledge base revolves around what is missing within the organizational element, such as the legislation, and the overall planning process. This also covers the element of profit, since an organizational set-up must be used to facilitate the development and organize the composition of ownership within the value chain of CCUS infrastructure. The organization aspect is an essential part of deciding how the implementation of CCUS infrastructure is planned for, and what kind of planning process that is needed and sought after by the involved actors. Several actors wish for more involvement by the public sector. This is opposed to an implementation based on market forces, where individual actors initiate CCUS projects and transportation – by relying on the public sector instead, a holistic planning of the CCUS infrastructure could be ensured.

# Discussion 10

The aim of this chapter is to highlight the elements that have had the most significant effect on the outcome of this report, and discuss how changes in these could impact the results.
The key methods of the report are discussed in terms of how these aid in data collection and the path towards the results. Furthermore, elements that can determine the future process of the implementation of a CCUS infrastructure are discussed.

## 10.1 Primary Methods for Evaluating CCUS Infrastructure

The methodological approach of this report consists of a range of methods to increase validity of results. The aim of the report is to investigate the socio-economic feasibility of CCUS infrastructure in Northern Jutland where both the spatial, economic and planning aspects are investigated and different methods aid in evaluating each aspect.

### 10.1.1 Evaluation of Planning Approach

The planning aspect has mainly been investigated by data collection through interviews of different actors within the CCUS value chain. The interviewees were mainly selected on the background of their representation in the CCUS value chain, which to a certain degree is fully represented with the interviewees. One aspect that could increase the validity of the results, as well as correlate the spatial and economic evaluation with the implementation analysis further, would be selecting interviewees that have a higher knowledge of Northern Jutland. Thus, the implementation would be more concerned with the proposed scenarios and not only CCUS infrastructure in general. An example is the interview with an employee from the Danish Energy Agency. The interviewee's knowledge of Northern Jutland is limited which resulted in the questions being answered on a general and national background. Additionally, the questions that were asked in all interviews, were not strictly based on the scope of Northern Jutland which have led the interviewees to answer on a more general background. The interview guide that leads the questions is included in appendix A.11. This could have led the results of the interviews to be less valid in the relation to Northern Jutland. On the contrary, the questions related to the implementation of CCUS infrastructure, does not differ in a broad extent throughout Denmark, since the same issues, such as legislative guidelines are the same regardless of geographic location.

### 10.1.2 Tool for Spatial Analysis

The spatial aspect is in this report investigated through the use of GIS and especially the 'Path planner' tool. The choices made in this tool resulted in interconnected networks to be formed. This means that both sinks and all point sources are connected in the networks. The output in form of networks thus differs from what several of the interviewees believe will be a feasible infrastructure for $CO_2$, which is a network that consist of larger transmission lines and minor distributions lines. Creating such a network could potentially result in a more effective network since the capacity of the pipelines would be optimized rather than the distance of the pipelines as currently. The network would prioritize shorter distances with a large capacity, rather than including all point sources and only optimizing regarding the distance of route. The path planner tool does not optimize on cost through optimal pipeline capacity, and thus means that even though the shortest routes between point sources and sinks are found it is not necessarily the network with the lowest costs. This difference between what the interviewees believe is an optimal infrastructure, and the results in this report, increases the uncertainty of the results. Additionally, the GIS tool that is used for the spatial analysis has a large impact on the outcome, meaning that this can be alternated to follow the expectations of the interviewees in the CCUS value chain. Therefore, further iterations of the use of this tool is encouraged in order to find other optimal routes – and perhaps more effective. The iteration could exist in finding transmission lines routes and thus create a network which correlates with what is expected from the actors within the CCUS value chain.
Another aspect of the spatial analysis is the use of the road network as input for the path planner tool. Utilizing a network is a prerequisite for using the tool, and thus means that all of the routes in the network are bound to follow the roads, even though there might be a possibility of shorter distances when placing routes in a straight line. Another input that could be used as a network dataset, would be the existing natural gas network. Since there has been a discussion of whether the network can be reused after natural gas is decommissioned, this could be used to determine routes for $CO_2$ pipelines, where the road network is suited for truck transport. The benefits of using the existing road network, is that there is a high chance that it is possible to place pipelines. However, this uncertainty of pipeline length has been investigated in the sensitivity analysis, and shows that this does not have a large impact on the results. Another aspect of the output of the path planner tool is the routes for truck transport. The routes follow the network routes where the object is to find the shortest distances for the overall network. This does not mean that the shortest path for each truck route to injection point on the pipeline is found. This is a simple way of estimating truck routes. This could be changed by using another GIS tool to find the shortest paths of each truck route, and thus circumventing the output from the path planner tool. This increases the uncertainty of the results from the path planner tool. The cost of truck transport does not make out a large part of the costs, only 1-2% of cost per ton, but is nonetheless an ineffective way of transporting the $CO_2$ and therefore the routes for truck transport are not realistic.

### 10.1.3 Distinction of Fossil and Biogenic $CO_2$

A part of the methodology for configuring the CCUS infrastructure was the choice of not distinguishing between fossil and biogenic $CO_2$. Not all interviewees agree that this is

important but the main position to this subject is that it is decisive for any development related to CCUS infrastructure. This is especially significant for the utilization of $CO_2$ in the production of e-fuels, as highlighted by Lindeloff [2023]. In order for the e-fuels to be RED II compliant, and being sustainable, they have to utilize biogenic $CO_2$ [European Commission, 2021b]. The future role of certificates determining the origin of the $CO_2$ is highlighted by the interviewees in terms of biogenic $CO_2$. This is also an incentive to include smaller point sources, such as biogas plants, that will ensure a higher supply of biogenic $CO_2$.
The distinction of biogenic and fossil $CO_2$ could impact the results of this report as a large amount – 1.2 mil. ton $CO_2$ a year – of the captured $CO_2$ in each scenario is utilized for e-fuel production. The results do not show this distinction and it is therefore unknown whether the share of biogenic $CO_2$ is high enough to cover the estimated demand of the PtX projects. However, it is relevant to mention that most of these projects will be commissioned closer to 2030 which means the share of biogenic $CO_2$ is expected to be higher, due to increased biogas production [Lund et al., 2021].

## 10.2 Results of Spatial and Economic Evaluation

The three scenarios are based upon two different levels of $CO_2$ emissions – two scenarios with point of departure in current emissions and one based on emissions in 2045. This has a significant impact on for instance the investment in capture units, which means that scenario C in this regard seems less costly due to a decreased investment. However, the lower quantity of $CO_2$ also makes the network more expensive due to the lower quantity of $CO_2$ in the pipelines. Nonetheless, these two different emission starting points make it difficult to compare the scenarios and benchmark them against each other.
Yet, the scenarios are compared in order to show how the different $CO_2$ quantities impact the feasibility of a CCUS infrastructure, and it can thus be concluded that larger and fewer point sources in scenario B overall is the most feasible scenario. However, the setup of the scenarios does not disclose the correlation between size of point sources and the distance to the high capacity pipelines. This analysis determines that the larger point sources in scenario B are basis for a feasible infrastructure. It is however not known whether a shorter distance to smaller point sources also would be feasible and thereby if the size of CC plants or the length and capacity of routes are deterministic for the feasibility of the infrastructure. Furthermore, increasing the price of $CO_2$ emission allowances, lowering the discount rate and lowering investment costs benefit scenario C, which otherwise is the least socio-economic feasible scenario. However, these elements are all subject to change and thus questions whether these factors are too uncertain for the scenario to determine if the scenario will become feasible in the future.

The economic evaluation is not based upon a comparison with a baseline scenario, where no change is the objective, which is usually an essential part of comparing alternatives when focusing on choice awareness. It is difficult to set up such a scenario since the CCUS infrastructure would be a whole new entity in the general infrastructure setup in Denmark. The NPV and the socio-economic results should be seen in the light of this, because it is not possible to compare the situation to a baseline scenario. So in all cases it would be an additional expenditure. However, there is a discussion of whether it is affordable to

not invest in a CCUS infrastructure since one of the main points of this is to avoid $CO_2$ emissions that otherwise contribute to global warming and climate changes, and a certain amount of carbon capture is needed to fulfil the emission reduction goals.
The costs of the scenarios can therefore be compared with the price of $CO_2$ emission allowances as trading with these is the only other alternative to the CCUS infrastructure. The impact of the price of $CO_2$ emission allowances compared to the cost of $CO_2$/t are depicted on figure 10.1, which shows that the price of the $CO_2$ emission allowances of 99.1€ per ton (2030 prices according to The Danish Energy Agency [2022]) can pay for the CCUS infrastructure.

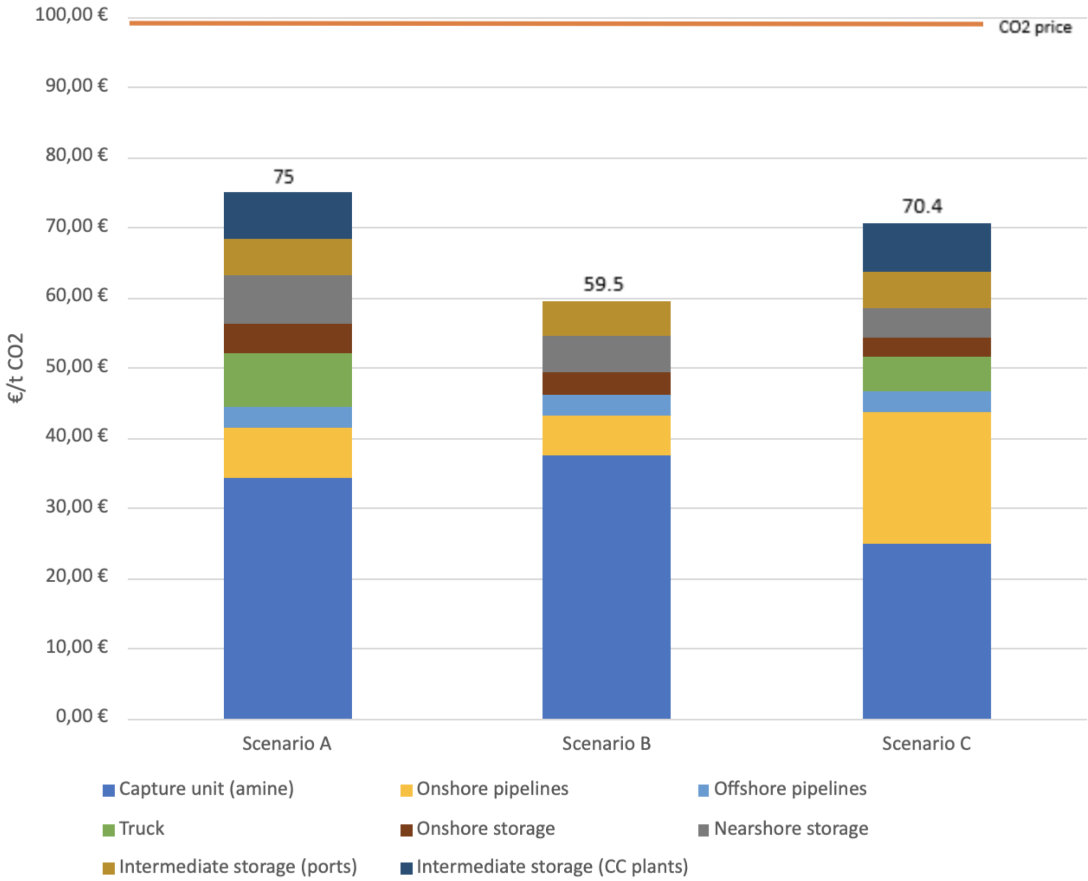


**Figure 10.1.** Cost/t $CO_2$ in each scenario, highlighting the price of $CO_2$ emission allowances at 99 €/t $CO_2$.

A basic term of the evaluation of the CCUS infrastructure, is the uncertainty of every aspect of the infrastructure, including all the costs that are part of the economic evaluation. Other uncertainties relate to the technical feasibility of the components of the CCUS infrastructure which can also increase the cost of the infrastructure. Some of the economic uncertainties are investigated in section 8.5. One of these are the investment costs of each technology, which is investigated through a high and low sensitivity that shows the range of the costs which each scenario can be expected to fall under. However, it could be more realistic to expect that the investments would change between high and low in the same scenario and not only be either high or low. Moreover, the infrastructure will most likely be constructed over time, which means that the total investment will not be placed in

the same year but spread over several years and gradually increased over time. This can impact the feasibility of the CCUS infrastructure in both negative and positive directions. All scenarios utilize 2030 cost levels for investments, but some investments could be made subsequently where the costs would be lower according to The Danish Energy Agency [2021e]. An aspect that affects the sensitivity analysis, is that mostly the same elements are included in each scenario – this means that regulating the input does not have a large effect on comparison of the scenarios, as it would if the scenarios included different technologies.
The scenarios investigate a future where the quantities of $CO_2$ is only based on emissions in Northern Jutland and where the assumption is that the CCUS infrastructure is a closed system. This impacts who are expected to invest and how the expenses are split between actors. As plans of importing $CO_2$ to Northern Jutland has been announced, an assumption of the split between who pays for the CCUS infrastructure can be expanded [Port of Aalborg, 2023]. If import of $CO_2$ for storage is considered for the CCUS infrastructure, more actors will be involved and the investment will be split between these additional actors. This increases the feasibility of the CCUS infrastructure.

The results of the economic evaluation and the related sensitivity analysis shows that scenario B capturing $CO_2$ from point sources above 40,000 ton $CO_2$ a year is the overall most feasible scenario both in terms of socio-economic effects and cost per ton. This shows that the additional infrastructure in terms of trucks, smaller pipelines and capture units are redundant, and that it is not feasible to capture smaller quantities of $CO_2$. Therefore, it would be relevant to investigate where the lower threshold of the capacity of the point sources should be.
Nevertheless, the sensitivity analysis indicates that the price of $CO_2$ emission allowances has a significant impact on the feasibility of the scenarios, which shows that this aspect is decisive for CCUS infrastructure implementation and is an aspect that need attention to ensure the implementation to ensure that it is not too low and thereby decreases the feasibility of investments in CCUS infrastructure.

## 10.3 Future Perspectives of Implementation of CCUS Infrastructure

In the previous analyses, it has been highlighted that there is a high uncertainty present in the development and implementation of a CCUS infrastructure which impacts the future perspective of CCUS. In this section, some of these uncertainties regarding the way a CCUS infrastructure is implemented, and the proposed scenarios of this analysis, will be discussed.

### 10.3.1 Geographical Scale

The geographical scope of Northern Jutland that is applied to all scenarios. This was chosen because of the amount of current and expected biogas plants, as well as the location of the country's largest $CO_2$ emitter, Aalborg Portland. This has from the onset of the analysis limited the amount of point sources, sinks and network routes. This means that the proposed network assumes that transportation of $CO_2$ will happen in "clusters" with individual networks if viewed on a national scale. As it was pointed out in the previous chapter by Damtoft [2023], there could also be a need for a combined national network and even an international connection to neighbouring countries. If this analysis was made on a national scale, it would require a larger analysis of all point sources in Denmark and also all sinks. The network path planner could have been used with the Danish road network, and made a combined network. The selection of routes where truck transport should be used instead of pipeline would then have been more substantial. An alternative to making scenarios for the whole country could be to add points as import and export from and to the rest of the country. This would however also require data for how much $CO_2$ that would be transported to Denmark from other countries, and how much $CO_2$ that would be captured from point sources in the rest of Denmark and sent to Northern Jutland. The same analysis approach could be used in a larger scale, and would in this project have resulted in a larger, more complex network.

### 10.3.2 Future Expectation of Point Sources and Sinks

In this analysis, the selection of point sources that are included in the network are chosen based on their prospect of electrification based on their current combustion methods and process temperatures. Furthermore, the PtX sinks that are included in all scenarios are based on planned projects that have not been constructed yet. The scenarios of the analysis were based on including different sizes of point sources because there is an uncertainty in how large the point sources can be, for it to make sense to capture $CO_2$ from it.
Another aspect of uncertainty in this regard, is which point sources that in reality can or will be used for carbon capture in the future. It is assumed that all the point sources without a high temperature process will be electrified by 2030, which is the year the scenarios has as their outset. As with several other developments towards a fossil free emission, there could be a delay in terms of when this transition will happen, and it might not happen for all point sources at the same time. Therefore, there could be more point sources that could be taken into account when planning for a CCUS infrastructure. This could have affected the design of the infrastructure and thus have consequences for the economic evaluation, as it could be seen in Scenario A, that more point sources do not necessarily equal a better economic feasibility. As it was described in the previous chapter, there is also an uncertainty in when different point sources will be connected to the infrastructure, and some point sources could possibly be connected for 10 years and then be electrified or stop operation. These are elements that are not included in the analysis or sensitivity analysis and are thus uncertainties that are difficult to forecast. This means the $CO_2$ quantities of Scenario A and B are potentially overestimated and optimistic in terms of what can be captured. This can impact the feasibility of the scenarios as the quantity of the $CO_2$ impacts feasibility as scenario C is not feasible but has the somewhat same infrastructure elements as scenario A but lower quantity of $CO_2$.
The PtX sinks of the analysis also have a degree of uncertainty connected to them, as they are based on plans for projects that all are in different stages of the planning process. Some are announced as projects and have applied for various permits, but none of the projects have final environmental and building permits. Therefore, there is a chance that some of the projects might not be realized. Alternatively, if the projects are constructed, the finalized projects could have different capacities than planned for, and thus not need

the same amount of $CO_2$. This could affect the sizing of pipelines and would thus have consequences for the economic analysis.

### 10.3.3 Choice Awareness

The choice awareness theory has been used as a guide for the analysis, and especially in the analysis of how the CCUS infrastructure should be implemented. This was done because the theory guides how a new technology is planned for and implemented in a sustainable way, where different choices are presented equally.
The different scenarios of this analysis has shown different physical ways to plan for or outline a CCUS infrastructure, however, it can be argued that this does not represent a *true choice*, since other technologies are not examined in this report. This was also emphasized in section 6.1. The result of this report's analysis does not come up with different choices that have been analyzed equally, but more so one choice that can be applied in various ways. The way choice awareness is also utilized, is to investigate how a successful implementation of this radical technological change can look. Here it was found that the organizational aspect has a large impact on how this specific technology can be ensured a sustainable implementation. For other technologies, other elements such as the technique can have the largest impact in terms of implementing the technology. Investigating the implementation by using the five elements of technology has proven to cover all different aspects of the technology when determining where there is a lack of development within the technology's concept, such as the organizational framework and where there is a steady foundation, which is showcased with the amine carbon capture technique.

### 10.3.4 Subsidies and Funds

Another point that is emphasized from several actors in the previous chapter, is that there is a wish for financial aid. Currently, there are two funds that can be applied for. Another approach could be that the Danish Government gave subsidies to different elements of the value chain. According to the CCS strategy by Socialdemokratiet et al. [2021], the funds will eventually be replaced by subsidies and taxes that will compensate for the investments. One thing that is not analyzed in the economic evaluation is the individual companies' business cases for entering into or becoming a part of a CCUS infrastructure. Dahl [2023] mentions that the business case for the biogas companies depends on, if the cost for capturing $CO_2$ and transporting it to a consumer is higher or lower than the price the $CO_2$ can be sold for. If the point source companies receive subsidies for the amount of $CO_2$ that is captured, the requirements for the business case would be easier to meet. Another way of viewing this is from the offtaker's side. As Lindeloff [2023] mentions, it has to be cheaper for the PtX developer to buy $CO_2$ from the combined network rather than if they transport it themselves, for the combined infrastructure to be a feasible solution. In this report, business economic analyses from the emitter or offtaker's point of view have not been made, since there still are uncertainties in the set up of ownership and responsibility of investments.

There is also the possibility that the development would be market-driven and not based on the government's financial involvement. An example of this is the recently announced project by Fidelis New Energy and Port of Aalborg, where $CO_2$ will be imported to and consequently transported to a storage or utilization site [Port of Aalborg, 2023]. The company proclaims to be making investments for over 2 bil. EUR when the project is built in 2026 [Port of Aalborg, 2023]. Whether this project will include pipeline or truck transportation of $CO_2$ is not clear, but this could be an example of a company that initiates the implementation of CCUS infrastructure without the involvement of the state. This differs from what is otherwise stated by the interviewees as they stress that the infrastructure should be state owned.

### 10.3.5 Planning Process

When looking at the planning process of CCUS that is currently happening, and comparing this to the analysis in this report, it is interesting to note that the analysis of the actors that are involved in the value chain of a CCUS infrastructure, point to a wish for the government to make overall plans and take financial initiatives to instigate the implementation of CCUS infrastructure. This is partially being done via the funds that will be given to Ørsted, and through the overall policies that the government has laid out for CCUS in Denmark even though this project also includes a private investment from Microsoft. The project from Ørsted will capture 0.43 mil. ton $CO_2$/year compared to the government's wish for at least 0.4 mil. ton/year from 2025, which later will be up to 0.9 mil. ton/year. According to Lund et al. [2021] up to 5 mil. ton $CO_2$ should be stored from 2030 to reach climate neutrality in 2045. This is a significant difference from the goals of the government. These goals for the government's tenders can risk that other developers will not engage in the implementation of CCUS infrastructure, if only few actors can participate in the public funding. These elements resemble a top-down process of planning, that has its point of departure in the government's initiatives, where the market will develop under the guidelines that the government has set.

Another input to this discussion, are the plans that Fidelis New Energy and the Port of Aalborg has announced. In this case, a private actor has initiated their own project and does not wait for a common plan for all of Denmark, before the projects is planned. This is an example that resembles a bottom-up process. The bottom-up process is expected to be supported by e.g. the municipalities and Green Hub Denmark who for instance are partaking in the CO2Vision project that is partially about creating a strong value chain across all actors involved with CCUS infrastructure and thus adding to the bottom-up process. As it was explained by some actors in the analysis of implementation, there is also the possibility that the market itself will begin to develop projects individually and that the market then will regulate the price of $CO_2$ and find a solution as to how to transport it.

The effect that a mix of these processes can be that the market and the state will influence each other, and that this will have a positive effect on future policies, as there will be experiences from the actors involved that can be considered when determining the future regulation regarding this sector. On the other hand, there is a risk that if the market begins to set up projects without a common guideline, that there will be a lot of transport of $CO_2$ across the country from specific sources, to specific sinks. This could lead to a higher socio-economic cost, where a common investment could spare the users of the infrastructure some costs. The actual development seems to be a weigh off between how long it takes for the government to start the initiatives that are wanted by the actors, and how long the actors can wait before they take the development and implementation into their own hands.

# Conclusion 11

This report has investigated potential arrangements of a CCUS infrastructure in Northern Jutland, constituted by routes that follow the existing road network, based on different capacities of $CO_2$ emissions of point sources and modes of transportation which has resulted in three scenarios; Scenario A with point sources above 1,000 ton $CO_2$ a year, Scenario B with point sources above 40,000 ton $CO_2$ a year, and lastly, Scenario C with point sources above 10,000 ton $CO_2$ a year which is based on emission reductions in 2045 as anticipated by Lund et al. [2021].
All scenarios prioritize the $CO_2$ demand of proposed PtX projects in Northern Jutland, and sends the remaining $CO_2$ to ports, and nearshore & onshore long term geological storage. For nearshore storage, offshore pipelines are proven to be the most feasible transport solution compared to ship transport.

The spatial and economic evaluation of potential CCUS infrastructures in Northern Jutland highlights Scenario B as the most feasible scenario based on the lowest annual cost per ton $CO_2$ which is 59.5 €/t $CO_2$ and the highest socio-economic benefits in terms of a net present value of 894 million € with a timeline of 30 years. The scenario is the most economically feasible due to the overall reduced investments in all technologies compared to the other scenarios. Especially, the cost of intermediate storage at point sources where truck transport is needed is redundant in this scenario since all point sources and sinks can be connected in a pipeline network. Furthermore, the large quantities of $CO_2$ benefit the scenario, because the point sources over 40,000 ton $CO_2$ a year constitute the largest point sources in terms of individual $CO_2$ emissions in Northern Jutland.
An important aspect of the scenarios is the $CO_2$ price of sold $CO_2$ emission allowances that drives the feasbility of scenario A and B and generates a positive NPV. This price is based on 2030 levels of the socio-economic $CO_2$ emission allowance cost for a changed $CO_2$ emission. This means that the future infrastructure has a positive socio-economic impact with the included factors.

The implementation of CCUS infrastructure relies on support in terms of a positive legislative environment and financial support from the state. Furthermore, interviews with actors within the CCUS value chain indicate that state owned entities should be initiators and owners of a potential pipeline system. This is to ensure a legitimate process of implementation. The organizational conditions have a large impact on how the CCUS infrastructure should be implemented in terms of this being the main barrier for further implementation in a timely matter, since CCUS is expected to be a contributor in reaching the climate goals in 2030. Several actors within the CCUS sector wish for more clear regulative and legislative guidelines for development of CCUS, which highlights the value of a structured organizational aspect in this technology. Furthermore, a holistic view on the planning of CCUS infrastructure would benefit the implementation of CCUS as this would aid in the certainty of all aspects of the technology being accommodated.

It can be concluded that a vital part of planning for the CCUS infrastructure in Northern Jutland is reducing some of the uncertainties related to the development of the infrastructure. Some of these uncertainties are related to investments costs and $CO_2$ price which have an impact on the business case of CCUS infrastructure. The uncertainty can be mitigated by ensuring an economic aid through e.g. financial pool and subsidies for CCUS projects. Another aspect of uncertainty is assigning guidelines and pathways for Danish CCUS development which could be aided through elaboration and clarification of the CCS strategy, supported by legislative and regulative initiatives by the Danish state. It is evident that the spatial planning aspect related to the configuration of the CCUS infrastructure needs to be investigated through several iterations of spatial analyses in order to optimize the arrangement of the CCUS infrastructure.
Conclusively, the proposed CCUS infrastructure has a positive socio-economic impact and the actors involved in the CCUS infrastructure are ready for the development, meaning that it is pertinent to get started on the implementation process towards a future with CCUS infrastructure.

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# Appendix A

## A.1 Input for Economic Evaluation

| Input | # | Unit | Source |
|---|---|---|---|
| Discount rate | 3.5 | % | [The Danish Ministry of Finance, 2021] |
| Net taxation factor | 28 | % | [The Danish Energy Agency, 2021d] |
| Tax distortion factor | 10 | % | [The Danish Energy Agency, 2021d] |

## A.2 Price of CO2 Emission Allowances

| **Price of CO2 emission allowances (2030)** | | |
|---|---|---|
| *Price* | *Low* | *High* |
| 99.1 €/ton CO2 | 79.3 €/ton CO2 | 204 €/ton CO2 |

## A.3 Amine Post Combustion Carbon Capture

| | **100 MW(th) WtE or biomass CHP plant** | **500 MW(th) biomass-fired boiler** | **4500 ton clinker/day cement kiln** | Unit |
|---|---|---|---|---|
| **Investment** | 2,7 | 2,3 | 2,6 | mill € / [t $CO_2$/hour] |
| **Fixed O&M** | 0,081 | 0,069 | 0,078 | mill € / [t $CO_2$/hour] |
| **Variable O&M** | 2,5 | 2,5 | 2,5 | € per t $CO_2$ |
| **Startup** | 25 | 25 | 25 | € per startup/ [t $CO_2$/hour] |
| **Lifetime** | 25 | 25 | 25 | years |

## A.4 Ship Transport

| | **Ship transport (4000 t $CO_2$, year 2030)** | **Ship transport (10,000 t $CO_2$, year 2030)** | Unit |
|---|---|---|---|
| **Inv.** | 9500 | 6200 | EUR/t $CO_2$/y |
| **fixed OM** | 475 | 310 | EUR/t $CO_2$/y |
| **variable OM** | 0 | 0 | EUR/t $CO_2$/y |
| **Lifetime** | 40 | 40 | years |

## A.5 Road Transport

| | **Truck transport (30 t liquid $CO_2$)** | Unit |
|---|---|---|
| **Fixed OM** | 3,8 | EUR/t $CO_2$ |
| **Variable OM** | 0,14 | EUR/t $CO_2$/km |
| **Lifetime** | 10 | years |

## A.6 Pipeline Transport

| | **Onshore single line, 10 - 30 t $CO_2$/h** | **Onshore single line, 30 - 120 t $CO_2$/h** | **Onshore single line, 120 - 500 t $CO_2$/h** | **Offhore single line, 120 - 500 t $CO_2$/h** | Unit |
|---|---|---|---|---|---|
| **Inv.** | 15 | 8 | 2,3 | 4 | EUR/ [t $CO_2$/h]/ m |
| **Fixed OM** | 20 | 20 | 20 | 20 | EUR/ [t $CO_2$/h]/ year/km |
| **Lifetime** | 50 | 50 | 50 | 50 | years |

## A.7 Onshore Storage

| | **Onshore 1 Mt/y** | **Onshore 3 Mt/y** | **Onshore 5 Mt/y** | Unit |
|---|---|---|---|---|
| **Inv.** | 2,67 | 2,05 | 2,14 | EUR/ t $CO_2$ |
| **Fixed OM** | 3,4 | 1,21 | 0,78 | EUR/ t $CO_2$ |
| **Lifetime** | 30 | 30 | 30 | years |

## A.8 Nearshore Storage

| | **Nearshore 1 Mt/y** | **Nearshore 3 Mt/y** | **Nearshore 5 Mt/y** | Unit |
|---|---|---|---|---|
| **Inv.** | 6,85 | 4,01 | 3,54 | EUR/ t $CO_2$ |
| **Fixed OM** | 5,10 | 1,78 | 1,11 | EUR/ t $CO_2$ |
| **Lifetime** | 30 | 30 | 30 | years |

## A.9 Intermediate Storage

| | **3,000 t CO2 terminal** | **14,000 t CO2 terminal** | Unit |
|---|---|---|---|
| **Inv.** | 2300 | 1400 | EUR/t CO2 |
| **Fixed OM** | 69 | 42 | EUR/t CO2/year |
| **Lifetime** | 25 | 25 | years |

## A.10 Investment Cost

| **Technology** | **Low** | **High** | **Unit** |
|---|---|---|---|
| Capture unit (amine) | 2.5 | 5 | mil EUR/[t CO2/hour] |
| Pipeline (10-30 t CO2/hour) | 12 | 20 | EUR/[t CO2/h]/m |
| Pipeline (30-120 t CO2/hour) | 6 | 10 | EUR/[t CO2/h]/m |
| Pipeline (120-500 t CO2/hour) | 1.8 | 3 | EUR/[t CO2/h]/m |
| Offshore pipeline (120-500 t CO2/hour) | 3 | 7 | EUR/[t CO2/h]/m |
| Ship (10,000 ton CO2) | 5,000 | 6,500 | EUR/t CO2/year |
| Intermediate storage (3,000 ton CO2) | 2,000 | 3,000 | EUR/t CO2 |
| Intermediate storage (14,000 ton CO2) | 1,200 | 1,800 | EUR/t CO2 |
| Onshore storage (5 mt CO2) | 1.85 | 2.85 | EUR/t CO2 |
| Nearshore storage (5mt CO2) | 3.09 | 4.79 | EUR/t CO2 |

## A.11 Interviewguide

| **Subject** | **Notes** |
|---|---|
| Structure | Arrangement of modes of transportation, location, actual CCUS needs, and actors’ influence on certain decisions |
| Utilization of CO2 | Storage vs utilization in PtX, biogenic and fossil CO2, emissions and needs for CO2 now and in the future |
| Kickstart of CCUS infrastructure | Initiators and initiatives for the development of a unified infrastructure |
| Ownership | Payment and ownership of carbon capture plants, pipelines, trucks and storage facilities |
| Legislation and regulation | Gaps and uncertainties in legislation |
| Knowledge related to technology, organisation, product and general knowledge base | Gaps and uncertainties in the knowledge base for development and implementation of CCUS infrastructure |

## A.12 Overview of Interview Responses

| Interviewee<br>Topic | Aalborg Portland |
|---|---|
| Technique | |
| *Topics:*<br>*• Configuration of infrastructure*<br>*• Who influences the infrastructure* | • An infrastructure plan should not only be regional but national and trans-national and connections with the rest of Europe<br>• There will be different types of emitters, where trucks will be for emitters below 50,000 ton CO2/yr and pipes for those who emit 50,000-100,000 ton co2 a year<br>• Storage options are not mature, which makes is very expensive |
| Product | |
| *Topics:*<br>*• Final infrastructure configuration*<br>*• Who can influence*<br>*• Utilization of CO2* | • An infrastructure plan should not only be regional but national and trans-national and connections with the rest of Europe<br>•A large part of the cost of construction is how the CO2 is transported and whether this is liquified<br>• It is a necessity to store the fossil CO2, but AP also has a great portion of biogenic CO2 usable for PtX<br>• There is great potential for industrial symbiosis/synergies between AP and PtX<br>• CCS is optimal so you get negative emissions, however a combination of CCU and CCS will probably be the best, both seems economic feasible. Underlines the need of a joint network (pipes) where emitters, storage sites and utilization sites are connected<br>• Very important for AP to distinct between fossil and biogenic CO2 - the biogas certificate system could be an inspiration to also ensure use for PtX |
| Profit | |
| *Topics:*<br>*• Who should pay and*<br>*• Who should own*<br>*• Business case* | • The government should plan for and own a pipe-infrastructure, so it is possible for emitters like AP to connect to this infrastructure<br>• It is possible to invest in a CC plant, however, it is not possible to earn back the investment today. However, they expect the price for emitting CO2 will increase in the future.<br>• Would need some sort of subsidy for the investment in CC plant, perhaps be inspired from Norway where the government gives a subsidy for the first 10 years and the government pays/plans for the CO2 infrastructure/network<br>• Complicated CO2 tax/qouta rules which in the future will make it more expensive for AP |
| Organization | |
| *Topics:*<br>*• Utilization of CO2*<br>*• Kickstart of CO2 infrastructure*<br>*• Initiatives for kickstart*<br>*• Business cases*<br>*• Legislation* | • The current CCS financial pool is not optimal since the emitter has to pay for an infrastructure, which does not make sense for AP (as a private actor). The risks are too high since there is a very early deadline, which entails fines if not kept<br>• The state needs to take the initiative, the market has shown that it does not have the ability to do so<br>• Evida is an important actor since they have knowlegde of working with gasses<br>•The kickstart could be a mix of publiv and private involvement<br>• The (low) maturity of technologies makes subsidies necessary<br>• Legislative problems related to when the ownership of the CO2 shifts when in a pipe network and then who is responsible when it is stored<br>• London protocol still makes rules for transport- something is missing<br>• A lot (legislatively) is still bound to EU regulation. But this is not up to date yet |
| Knowledge | |
| *Topics:*<br>*• Large knowledge gap* | • Knowledge of standardization of CO2 is missing<br>• Especially around the purity of the CO2<br>• There are different demands for the level of purity |

| Interviewee / Topic | Ammongas |
|---|---|
| **Technique** | |
| *Topics:*<br>*• Configuration of infrastructure*<br>*• Who influences the infrastructure* | • 10-15% of the flue gas has to be CO2<br>• Is somewhat correlated with emission (ton CO2/year), but the percentage is important due to CAPEX<br>• No current market for CO2<br>• Amine technologies can easily be put on a chimney, whereas the oxyfuel technology will be used for new plants |
| **Product** | |
| *Topics:*<br>*• Final infrastructure configuration*<br>*• Who can influence*<br>*• Utilization of CO2* | • Evida has made some calculations on this, the infrastructure will probably be a mix of technologies |
| **Profit** | |
| *Topics:*<br>*• Who should pay and*<br>*• Who should own*<br>*• Business case* | • Has participated in CCS bidding rounds as provider of technology, but does otherwise not have any suggestions here |
| **Organization** | |
| *Topics:*<br>*• Utilization of CO2*<br>*• Kickstart of CO2 infrastructure*<br>*• Initiatives for kickstart*<br>*• Business cases*<br>*• Legislation* | • E-fuels should be prioritized.<br>• All CO2 should be utilized whether or not it is biogenic or fossil<br>• Subsidy schemes should be targeted more directly<br>• The market is ready when offtake is secured. But it is the paradox of the 'chicken or the egg'. Some actors are already doing it<br>• Believe that the commercial market can overcome the regulation that might be missing<br>• Purity of CO2: they are right now cleansing the CO2 to a large extend. This CO2 is used for methanol production, so making sure that the CO2 will not be a problem in the production of e-fuels. Might change in the future, when it has been tested properly |
| **Knowledge** | |
| *Topics:*<br>*• Large knowledge gap* | • Cross field betwen desktop calculation and what is possible<br>• There might be a mismatch between TRL readiness and ambitions<br>• There has to be an alignment of interests in the development of CCUS |

| Interviewee<br>Topic | Biogas DK<br>(BP: Biogas Plants) |
|---|---|
| Technique | |
| *Topics:*<br>*• Configuration of infrastructure*<br>*• Who influences the infrastructure* | • Pipes are cheaper according to quantity<br>• Discrepansy of liquid vs gas in the pipes<br>• Configuration of different modes of transportation |
| Product | |
| *Topics:*<br>*• Final infrastructure configuration*<br>*• Who can influence*<br>*• Utilization of CO2* | • Configuration of different modes of transportation<br>• Trucks might be introduced first and then pipes. Truck transport is profitable now. Trucks are flexible which adds value to routes and sinks<br>• Future quantities for transport add uncertainties for dimensioning<br>• The ownership and payment should resemble current gasnetwork<br>• Important to distinct between biogenic and fossil CO2<br>• Prioritize capture on plants that cannot be electrified |
| Profit | |
| *Topics:*<br>*• Who should pay and*<br>*• Who should own*<br>*• Business case* | • BP are not willing to pay for hydrogenation if they have invested in other technologies first<br>• Cheap and very available source of biogenic CO2<br>• Evida/Government makes investment and adds tax/tariff level and then market will decide price of CO2<br>• Emitter pays for CC plant, the government and the market should make the investment attractive<br>• CLimate credits are uncertain and whether or not these can go to companies<br>• No market for 'selling' to either CCS or PtX<br>• The development and participation from BPs are dependent on whether or not there is a valid business case in it |
| Organization | |
| *Topics:*<br>*• Utilization of CO2*<br>*• Kickstart of CO2 infrastructure*<br>*• Initiatives for kickstart*<br>*• Business cases*<br>*• Legislation* | • Evida should pay for pipe infrastructure<br>• Capital need to come from the government to make it attractive to participate in CCUS infra<br>• User of network should pay off on the lifetime and use of network<br>• Cheap and very available source of biogenic CO2<br>• Government should take first step to kickstart CCUS development, however the market also impacts this<br>• Current NECCS pool does not favor the biogas plants because it is dependent on the developer to pay for the transport themselves |
| Knowledge | |
| *Topics:*<br>*• Large knowledge gap* | • The big picture is missing, since all technologies are known<br>• Logistics and orginazation of sale of CO2, perhaps some legislation<br>• What comes first? The market or the infrastructure? Who initiates |

| Topic / Interviewee | DGC |
|---|---|
| **Technique** | |
| *Topics:*<br>*• Configuration of infrastructure*<br>*• Who influences the infrastructure* | • Dependent on quantities and distances<br>• Trucks are good for smaller quantities<br>• Discrepansy of pressure level in pipes<br>• Carefulness of overdimensioning the system |
| **Product** | |
| *Topics:*<br>*• Final infrastructure configuration*<br>*• Who can influence*<br>*• Utilization of CO2* | • Network will consist of one or several large transmission lines and CO2 emitters can then connect to this in various ways depending on distance and capacity<br>• Fossil CO2 should to a wide extent be stored<br>• There are arguments for either storing and utilizing CO2 for e-fuel production - it is difficult to say what to go with |
| **Profit** | |
| *Topics:*<br>*• Who should pay and*<br>*• Who should own*<br>*• Business case* | • Many good intentions in the value chain, but someone has to make the risk. Support need to be present<br>• Evida could be owners of pipelines<br>• Get inspiration from existing natural gas setup to establish CCS<br>• Evida has authorization to go into this business<br>• But the ownership of the infrastructure will be mixed - the market will impat the competition<br>• Many business cases only exist if you can divide the CO2 in biogenic and fossil |
| **Organization** | |
| *Topics:*<br>*• Utilization of CO2*<br>*• Kickstart of CO2 infrastructure*<br>*• Initiatives for kickstart*<br>*• Business cases*<br>*• Legislation* | • Evida could be owners of pipelines<br>•CCS Pool is a good example of how DEA is supporting and driving the development further<br>• At some point there is no point in not developing a CC(U)S inrastructure - we already see the beginning with the Greensand project<br>• In some cases the State will begin the development and in other cases the private sector will instegate<br>• Safety Technology Authority has to look into the safety requirements of CO2 - the clear framework around these issues is missing<br>• The purity of CO2: are awaiting the EU commission to set specifik demands of purity. |
| **Knowledge** | |
| *Topics:*<br>*• Large knowledge gap* | • Demands of the pipenetwork including purity and quality of CO2<br>• Should not compare with natural gas - different processes<br>• It is a large puzzle of getting all the pieces of the CCUS infrastructure to fit together. WE don't know yet how it is supposed to go. So it is a balancing of starting earlier and that it might be more expensive |

| Topic / Interviewee | European Energy |
|---|---|
| **Technique** | |
| *Topics:*<br>*• Configuration of infrastructure*<br>*• Who influences the infrastructure* | • Location of $CO_2$ infrastructure can have an impact on where PtX sites will be placed<br>• Would rather transport the $CO_2$ is short as possible<br>• There are many factors yet to be decided of this subject<br>• Assumes the infrastructure will go to the larger ports in DK |
| **Product** | |
| *Topics:*<br>*• Final infrastructure configuration*<br>*• Who can influence*<br>*• Utilization of $CO_2$* | • Would generally be good with a $CO_2$ infrastructure. It would make the market easier, since there are many challenges linkes to sourcing of $CO_2$<br>• The transport of $CO_2$ is an important subject<br>• Would as an large offtaker of Co2 like to have an influence on design of the infrastructure, unsure whether or not they (the state/evida) will listen |
| **Profit** | |
| *Topics:*<br>*• Who should pay and*<br>*• Who should own*<br>*• Business case* | • $CO_2$ infrastructure is important but the economy/business case is also important<br>• If the ownership of the infrastructure impacts the cost of connecting to this to an extend where the business case of transporting the $CO_2$ themselves then it is a problem<br>•Should make an "account system" (afregningssystem), so it reflects the actual use of the infrastructure. Has to be economically more attractive than trucks<br>• Assumes it will be publicly owned, which makes sense in DK and ensures security of supply - on the other side perhaps a commercial control makes it more profitable<br>• There is a current dialogue of who should pay for the CC plants at the point source (since the $CO_2$ will be cheaper for EE) but some issues arise around the quality of the $CO_2$ |
| **Organization** | |
| *Topics:*<br>*• Utilization of $CO_2$*<br>*• Kickstart of $CO_2$ infrastructure*<br>*• Initiatives for kickstart*<br>*• Business cases*<br>*• Legislation* | • Challenges related to sourcing $CO_2$: regulation, certificates.<br>• Fossil/biogenic: the product is the same. But from 2034 the will be an EU injunction demanding the use of biogenic $CO_2$. Some of EE clients also demands the $CO_2$ to be biogenic due to their $CO_2$ account. If fossil $CO_2$ were to be used, you remove the incitament to reduce fossil emissions, so for society it is important to divide biogenic and fossil $CO_2$.<br>• Both the state and EU should kickstart the infrastructure. Tenders might no be the best option, but should do more 'nudging' to create a market. The state is responsible for building the infrastructure.<br>• There should be a collaboration on an EU level, so the goods can travel freely. $CO_2$ is right now seen as a waste product, which means it can't cross country borders<br>• Nudging means to create regulations in a way where it means that the participants in the market does not have any other choice but to store or utilize the $CO_2$<br>• Certificates are missing, like with biogas. Together with clear definitions on what is biogenic<br>• How to calculate the $CO_2$ emissions is also missing. Right now it makes more sense to store biogenic $CO_2$ rather than utilize it.<br>• A more holistic and broad view on the planning is missing, since CCUS is a part of securing e-fuel production.<br>• Large uncertainties of what future regulations/legislations there will be. A clarity of this is missing. |
| **Knowledge** | |
| *Topics:*<br>*• Large knowledge gap* | • First step is something where knowledge isn't missing, but the concept is: the technology to capture and cleanse the $CO_2$. Large scale demonstration is missing<br>• Uncertainties of how to conduct storage solutions<br>• The ttransport on land is rather known, but the transport between countries on ship is not<br>• Legislation: there are many uncertainties of the prices. The price of utilizing has to compete with storage. Uncertainties of how price drivers impact the cases, such as the negative emissions with storage of $CO_2$<br>• Uncertainties of where the infrastructure will be placed, and whether or not the timeline can be trusted - correlates with ensuring clients to the product |

| Interviewee / Topic | ENS |
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| **Technique** | |
| *Topics:*<br>*• Configuration of infrastructure*<br>*• Who influences the infrastructure* | • Pipelines are cheapest at some distances and quantities<br>• It is a challenge to dimension the size of the pipelines correctly - who will be connected now and later, and what amount will they deliver |
| **Product** | |
| *Topics:*<br>*• Final infrastructure configuration*<br>*• Who can influence*<br>*• Utilization of CO2* | • Focus on storage of CO2 first<br>• Fossil CO2 is easy to store long term<br>• All CO2 gives reduction in the climate score<br>• Focus on not having carbon lock-in by excluding certain point sources |
| **Profit** | |
| *Topics:*<br>*• Who should pay and*<br>*• Who should own*<br>*• Business case* | • There is an interest from the market in the voluntary climate credits<br>• It need to be decided who owns the network. It could be inspired by natural gas where a TSO have the overview, but no demand of whether it should be private or publicly owned<br>• There is interest in owning from Evida but also private companies. What is best has not been clarified yet. EU also need to decide something<br>• Private companies can store CO2 if they want (Subsoil Act)<br>• Prices of a CO2 network need to be public and third party access - DEA can set demands to a potential infrastructure |
| **Organization** | |
| *Topics:*<br>*• Utilization of CO2*<br>*• Kickstart of CO2 infrastructure*<br>*• Initiatives for kickstart*<br>*• Business cases*<br>*• Legislation* | • Pool is started for CCS, a later pool will also help utilization of CO2. Economic support is only given when the CO2 is stored in the ground<br>• There is a political focus on both storage and utilization<br>• For having a business case the CO2 quota price might not be enough<br>• It is challenge to get the whole value chain running<br>• Cluster collaborations are a part of kickstarting the development<br>• Question of an overall and guiding/coordinating political direction is missing or is the market ready to deal with it itself<br>• The rules are less rigid for a CO2 legislation (compared to other gasses)<br>• Apprenhension of creating too many rules if EU makes rules later on<br>• Perhaps more rules on competition on the area. Also environmental, safety and standards |
| **Knowledge** | |
| *Topics:*<br>*• Large knowledge gap* | • What comes first? State/political influence/instigation or the market on its own<br>• Finding out where pipes should be laid<br>• finding out if there is a knowledge gap on the transport legislation of CO2<br>• Perhaps more rules on competition on the area. Also environmental, safety and standards<br>• There is a lot of knowledge on the different parts of the CCUS infrastructure but the comprehensive chain of it is missing<br>• There is missing some regulatory knowlegde - some changes are underway<br>• Practical: standards are also missing (perhaps inspiration can be used from the northern lights project<br>• In a Danish perspective, having large CO2 pipes and storing undeground is rather new |

| Interviewee / Topic | Evida |
|---|---|
| **Technique** | |
| *Topics:*<br>*• Configuration of infrastructure*<br>*• Who influences the infrastructure* | • Having a transmission line which accumulates the quantities makes sense to a large extent<br>• Makes sense to utilize excess heat when the CO2 is compressed to liquid state<br>• Compressing to liquid state is very expensive (25-30 kr/ton) therefore gas state CO2 makes sense to a certain degree but the pipes also need to be bigger (and more expensive) when the CO2 is in a gasseos state |
| **Product** | |
| *Topics:*<br>*• Final infrastructure configuration*<br>*• Who can influence*<br>*• Utilization of CO2* | • The actual CCUS infrastructure is very dependent on the configuration (point sources), which is why it is difficult to assess a general configuration<br>• There has to be a business case but a communicative value is also part of it<br>• Need to open up more for utilization of CO2, but large incertainty in technologies for this (makes the business case vulnerable)<br>• Makes sense to focus on storage of CO2 now, and then the infrastructure can be retrofitted to also support utilization in the future<br>• There should be a certificate system to support the differentiation between fossil and biogenic CO2 |
| **Profit** | |
| *Topics:*<br>*• Who should pay and*<br>*• Who should own*<br>*• Business case* | • Important not to base the infrastructure on CO2 sources that will disappear within a reasonable timeframe<br>• Evida is a very possible initiator and owner of CO2 pipelines. They are open for private owning, but can't wait on this development in some cases. Potential for collaboration<br>•Evida can be coordinator with different 'sectors' of the CCUS infrastructure<br>• It makes sense that the government gives support but the investment comes from private companies (transport, storage operators and point sources) - no dependence o½n waiting for financial support |
| **Organization** | |
| *Topics:*<br>*• Utilization of CO2*<br>*• Kickstart of CO2 infrastructure*<br>*• Initiatives for kickstart*<br>*• Business cases*<br>*• Legislation* | • Evida is participating in many different projects, the hindrance is to make a concrete deal and making sure that the projects will happen<br>• DEA have a large impact and is a motivational factor (financial support pools)<br>• Evida is facilitating with support from the government<br>• Other initiatives are the cluster collaborations set down by the Danish Business Authority (knowledge collaborations)<br>• The initiatives should otherwise come from the industry (market) and Evida<br>• Regulation relating to ownership is missing. Evida is open for private actors can start up and own a pipeline which in the long term can be connected to Evida's (transmission) infrastructure<br>• Expropriation options is missing. CCS tender in 2026 is a very ambitious timeline<br>• Authority processing and negotiation with landowners takes time and if expropiation is not an option then this process will be prolonged<br>• Regulation can be inspired by natural gas legislation but difficult to compare CO2 ad natural gas since CO2 is not flammable |
| **Knowledge** | |
| *Topics:*<br>*• Large knowledge gap* | • Demands for CO2 standards: it is important that there is something to follow when designing the infrastructure (ISO27613 is related to design of pipes but is very strict) You need to have a standard that makes sense for emitters and transport operators and to use for putting it underground<br>• A lot of things related to legislation is undetermined<br>• A lot of things has to fit together (the whole CCUS chain)<br>• The quality of the CO2 is undetermined. Unknown which level of purity is acceptable without raising costs unnecessarily for either capture unit or sinks |

| Topic / Interviewee | Green Hub DK |
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| **Technique** | |
| *Topics:*<br>*• Configuration of infrastructure*<br>*• Who influences the infrastructure* | •The emitters wants pipes, so Evida or Energinet should lay some pipes. This i costly, so trucks may be an option for some emitters<br>• The infrastructure is dependent on whether or not CO2 will be imported or exported - a complicated subject |
| **Product** | |
| *Topics:*<br>*• Final infrastructure configuration*<br>*• Who can influence*<br>*• Utilization of CO2* | • Would make sense to have one larger transmission line, where emitters can be connected as to what makes sense<br>• Dimensioning of the pipes is a large uncertainty<br>• Necessary to have a perspective of the future as to who are the emitters - but a lot of uncertainty around this<br>• Expecting a certificate system to keep track of fossil and biogenic CO2 so the fossil CO2 will mainly be stored and the biogenic CO2 utilized for e-fuel production |
| **Profit** | |
| *Topics:*<br>*• Who should pay and*<br>*• Who should own*<br>*• Business case* | • Uncertainty of who should pay for the infrastructure<br>• The owner of the chimney will also pay for the capture unit<br>• Evida/energinet will probably own the pipeline network<br>• EU funds can support financing the infrastructure<br>• Many are waiting on the financial support and design of the infrastructure before they will start to capture the CO2<br>• The transportation of the CO2 is large unanswered question related to CCUS infrastructure<br>•Emitter will pay for storage<br>• The point of the CCUS infrastructure is perhaps not to earn money on it, but the value of capturing the CO2 is enough |
| **Organization** | |
| *Topics:*<br>*• Utilization of CO2*<br>*• Kickstart of CO2 infrastructure*<br>*• Initiatives for kickstart*<br>*• Business cases*<br>*• Legislation* | • Actors are waiting for framework conditions to be provided by the government/ministries<br>• Difficult to act and plan in a setting you don't really know, and this is connected to the fact that you don't know how the whole infrastructure will be built up<br>• Evida/Energinet will probably be initiators of a pipeline system<br>• A basic understanding of CO2 purity is missing<br>• If the CO2 should be liquified is also a question<br>• Uncertainty around the ability to apply for TM-E funds (EU funds)<br>• Uncertainty of whether their business case should only relate to the region (NJ)<br>• Uncertainty of which authorities should be involved<br>• The municipalities need to get started on their planning and authority processing<br>• Uncertainty of where the pipes should be laid<br>• Having someone decide which way to go is also missing<br>• It would help to have some more specific guidelines in the legislation, it would help those actors who otherwise are hesitant to act |
| **Knowledge** | |
| *Topics:*<br>*• Large knowledge gap* | • Many actors are willing to take action, and many have different knowledge and therefore also different opinions on the same topic - therefore it is difficult to make concrete decisions<br>• Roadmaps and test sites has to contribute to the knowledge base, the challenge is then to make decisions on the background of this<br>• Increase the qualification of people/workforce |