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Ocean Valley

Projecting the future supply and demand of carbon captured in the Oresund region until 2035

The unexplored potential of CCUS - new innovations dictating the way forward

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Novo Nordisk, Bill & Melinda Gates Foundations To Fund CO2-Into-Protein R&D Project

by Theodora Stankova · June 15, 2023 · 2 minute read

Denmark-based Novo Nordisk Foundation has joined forces with the Bill & Melinda Gates Foundation to provide DKK 200 million (approx. US$29 million) over a two-year period for a research and development (R&D) project aimed at creating a sustainable source of protein for human food derived from CO_2.

Source: Carbon Herald (2023)

Captura's Direct Ocean Capture Looks Promising

Erik Kobayashi-Solomon Contributor

Investor in climate change adaptation and mitigation businesses

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Feb 15, 2024, 07:15am EST

Capturing CO2 from Oceans - Captura

Through Direct Ocean Capture, Capturas removes CO_2 from the upper ocean, enhancing the ocean's capacity to draw more carbon from the air

Source: Forbes (2024)

Major Success For CCU: The Net Zero Industry Act Fully Recognizes CO2 Utilization As A Net Zero Technology

by Petya Trendafilova · February 26, 2024 · 2 minute read

The European Parliament and the Council of the European Union's recent agreement in trilogues on the Net Zero Industry Act (NZIA) **included CO2 utilization as an eligible strategic net zero technology**

Source: Carbon Herald (2024)

The following slides highlight the importance of addressing CCUS in public discussions, stressing the necessity for significant investments and tailored communication with policymakers to reduce GHG emissions in the atmosphere. Additionally, it is important to emphasize the pivotal role that future ports infrastructure must play as an interconnecting hub, facilitating the seamless exchange of resources and enabling efficient CCUS operations.

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Recommendations

- Build Collaborative Networks: Establishing collaborative networks with industry stakeholders, research institutions, start-ups, and international partners is essential for sharing knowledge and insights. Collaboration enables us to navigate uncertainties and stay informed about developments in the evolving carbon utilization landscap
- Look for Synergies between Denmark and Sweden: It is important to unite the differences between the two sides, instead of looking at Oresund as a divided region between Denmark and Sweden.
- Explore New Reutilization Cases: While leading multinational corporations heavily invest in CCUS technologies, some technologies remain immature and cost-intensive. It is important to explore new reutilization cases that may not yet be fully developed, leveraging innovation and collaboration to unlock their potential.

Executive Summary

In 2015, the Paris Agreement was enacted, establishing a maximum limit of 1.5°C above pre-industrial levels for global temperature increase. Achieving a global equilibrium between human-caused emissions and the capture of greenhouse gases in the latter half of the 21st century is crucial to meet this objective.

Carbon Capture, Utilization, and Storage (CCUS) is recognized as a pivotal component in achieving the goals outlined in the Paris Agreement. By capturing and storing greenhouse gases, such as carbon dioxide, CCUS technology plays a crucial role in mitigating climate change and limiting global temperature rise. Additionally, the utilization aspect of CCUS offers opportunities to repurpose captured carbon dioxide for various industrial applications, further contributing to emissions reduction efforts.

There are many uncertainties surrounding the development of business cases for CCUS, and this uncertainty discourages investments. Therefore, the Carbon Hub project will focus on clarifying these uncertainties by gathering provable data points, including assessing future use-cases for CO2. The study draws on open sources, interviews with CCUS experts, and available reports/studies

Conclusions

- The overall carbon supply in Oresund Region exceeds the demand for carbon multifold
- Importing carbon to Denmark could potentially increase future CO2 supply. However, much of the imported CO2 is expected to be stored in Danish underground storage sites due to their natural favorable characteristics.
- Currently, stakeholders primarily focus on Carbon Capture and Storage (CCS) rather than utilization, largely due to the prevailing CO2 reduction paradigm.
- Existing utilization cases include e-fuels, CO2-cured concrete, chemical intermediates, and future food protein. The carbon utilization market is anticipated to experience significant growth, potentially leading to the development of new use-cases.
- Electricity availability poses a limiting factor in most carbon utilization cases. Hydrogen is essential for producing e-fuels, but ensuring an adequate supply of green electricity can present challenges.
- While other utilization cases exist, it is still premature to provide a comprehensive overview of future CO2 demand.
- CCUS technologies are attracting increasingly substantial investments from large international corporations, indicating growing interest and confidence in these technologies.

Table of Content

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Navigating Supply and Demand Dynamics

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Lacking overview hindering investments
The lack of a comprehensive overview of both short and long-term supply and demand dynamics is a significant hurdle hindering investments in carbon hubs. The carbon market is still immature and insecure but movements in the CCUS (Carbon Capture, Utilization and Storage) industry indicate an escalating need for the capture and storage of CO_2 in the foreseeable future. Nevertheless, the focus extends beyond mere CO_2 storage; there is an acknowledgment that utilizing captured CO_2 holds significant, yet largely untapped potential. However, immediate efforts prioritize reducing CO_2 emissions before fully exploring its utilization potential. Numerous CCUS experts interviewed emphasized the importance of considering re-utilization but also highlighted the primary concern: ensuring the safe capture, transportation, and storage of CO_2 deep underground in reservoirs.

Not only does CCUS fuel the production of e-methanol, but it also finds applications in diverse sectors such as medical products, food production, and construction industry. This prompts a logical question:

Is there a more sustainable case for reutilizing CO_2 instead of consigning it permanently to underground storage, thereby enhancing the concept of circularity?

Breaking the CCUS value chain into small elements
The following sections draw on insights from Ocean Valley's CO_2 value chain model. This model, crafted through numerous interviews and engagements with CCUS experts, has evolved dynamically with continuous inputs, adjustments, and reaffirmations from project participants and experts. The purpose of this study is to decipher the complexities in CCUS and create a comprehensive overview of the carbon market, by shedding light, both qualitatively and quantitatively on each segment of the CCUS value chain model.
The goal is to fostering a more nuanced understanding of the CCUS value chain, demand and supply dynamics.

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Carbon Value Chain

Deciphering the complexities in the CCUS value chain

Navigating the Complexity: Unveiling the Carbon Value Chain Model

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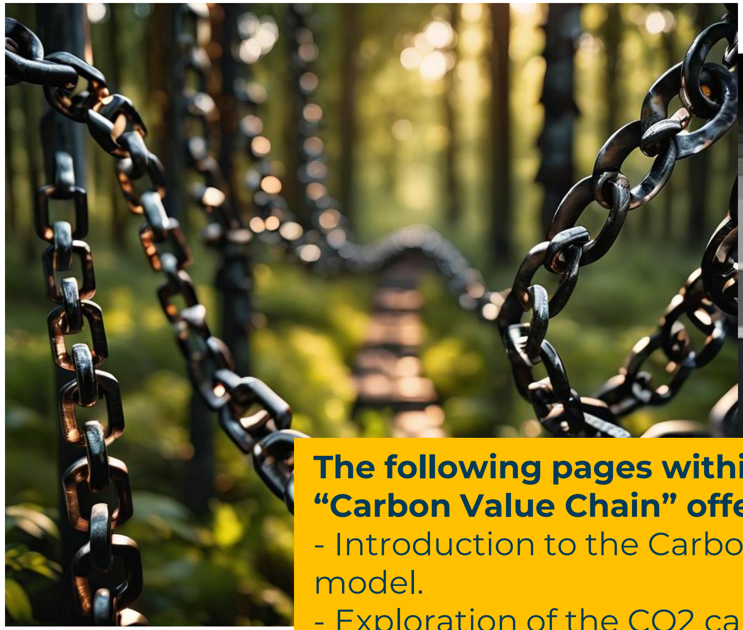
Why understand specific elements in the carbon value chain model?
Understanding the intricacies of the carbon value chain is paramount, given its complexity and the multitude of elements it comprises. The carbon value chain is context-dependent and continually evolves over time, influenced by technological advancements and shifting political ambitions. Despite, the relatively short distance between Sweden and Denmark, the carbon value chain is depicted differently because each value chain is unique according to geography, politics, technology and industry characteristics etc.

How has the value chain been developed?
The working group's strategy has involved breaking down the value chain into small individual components, offering an easy to interpret visual representation. This method not only brings a nuanced understanding of each element but contextualizes each element in a broader context.



The following pages within the section "Carbon Value Chain" offers an:
- Introduction to the Carbon Value Chain – model.
- Exploration of the CO2 capturing landscape
- Simplification of current Carbon Capture technology

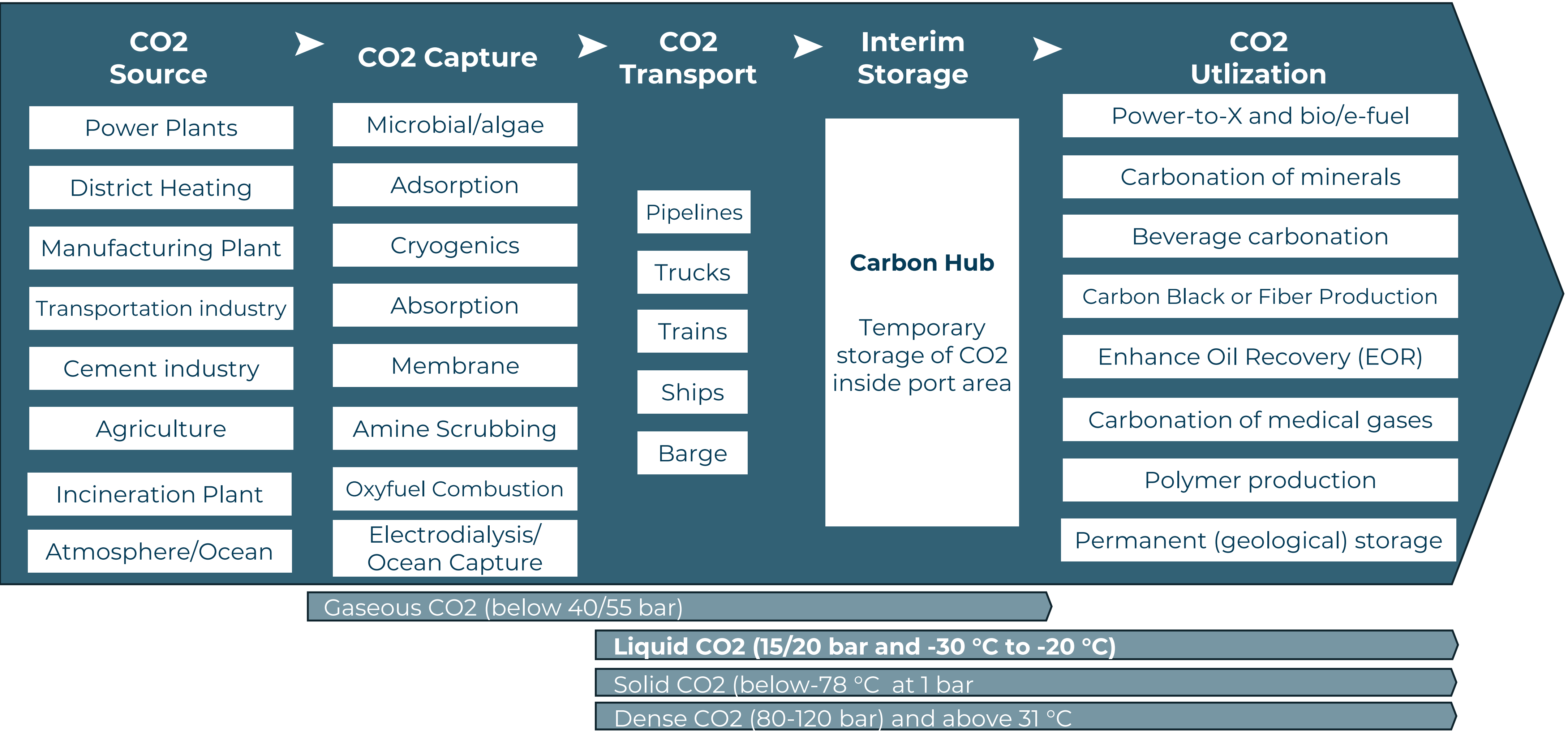
On the following page, you will encounter the value chain model crafted by the working group, a visual representation designed to elucidate the intricacies of carbon capture, utilization, and storage.

Decoding the Carbon Value Chain

The model encompasses **five key elements:** CO2 source, capture, transport, interim storage, and utilization. Arrows indicate the **four physical phases** of CO2 in this chain.

Peer-reviewed by CO2 experts, this collaborative model offers a comprehensive, though not exhaustive, view of the carbon value chain. It serves as a bridge between the broad landscape and the detailed intricacies of each element.

The following pages breakdown each component— source, capture, transport, interim storage, and utilization.



Understanding the landscape of CO2 sources

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Understanding the landscape of CO2 sources is a multifaceted journey, where diverse origins necessitate varied capture approaches. Numerous CO2 point sources contribute to the intricate web of carbon emissions. However, some sources emit more than others as shown below.

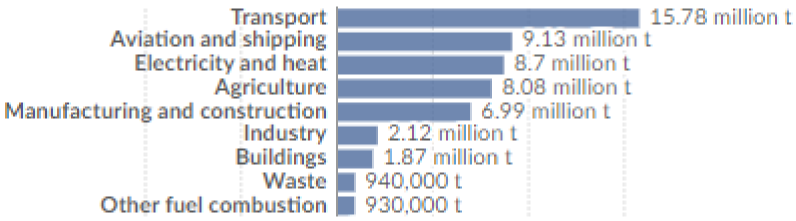
Why Focus on Point Sources?

Capturing CO2 is most economically viable when dealing with high concentrations, which are often found at point sources such as combustion facilities. At these facilities, the concentration of CO2 is sufficient to make capture feasible. Therefore, there is an emphasis on point sources over diffuse sources, as seen in the transportation sector or in the atmosphere.

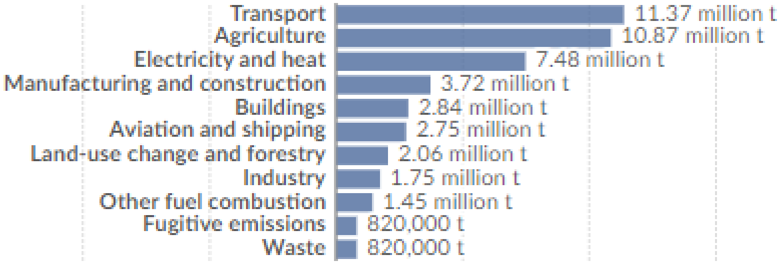
Unpacking the CO2 Capture Landscape

Presently, the primary focus of CO2 capture lies in certain key sectors, manufacturing plants, district heating, and power plants. These sectors represent prevalent point sources, aligning with the high concentration criterion necessary for economically viable capture.

Sweden – Total CO2 Emissions (2020)



Denmark – Total CO2 Emissions (2020)



Data source: Climate Watch (2023)

Major CO2 Sources

Power Plants: Combusting fossil fuels in power generation facilities releases substantial CO2 emissions.

District Heating: CO2 emissions result from the production of heat for residential and commercial use.

Manufacturing Plants: Industrial processes, such as chemical production, contribute significantly to CO2 emissions.

Incineration Plants: Waste incineration is another notable source of CO2 emissions.

Transportation Industry: Emissions from vehicles, planes, and ships constitute a major source of CO2.

Cement Industry: The cement production process releases substantial carbon dioxide.

Agriculture: Emissions arise from agricultural practices, including livestock and soil management.

Atmosphere and Ocean: While not directly point sources, the atmosphere and ocean serve as diffuse CO2 sources. Capturing CO2 directly from diffuse CO2 sources are logistically challenging due to relatively low CO2 concentrations.

Simplifying the many CCS technologies

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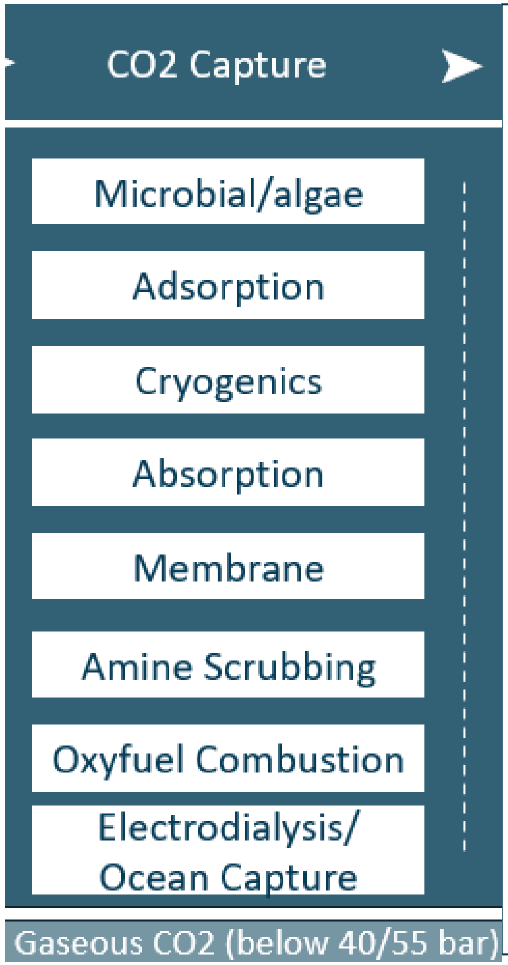
Carbon capture consists of the separation and concentration of CO2 from power and heat generation plants, or industrial processes. However, the separation and concentration of CO2 can be done in different ways according to the context. It is estimated that the use of carbon capture would address up to 32% of global CO2 emissions reduction by 2050. More than 28 Gt of CO2 could be captured from industrial processes until 2060, the majority of it from the cement, steel, and chemical subsectors. CCS and CCUS technologies are developed slowly, mainly as a result of high costs and unsupportive policy and regulatory frameworks in many countries. (Refuge et al., 2021)

The most common process used to capture CO2 is to separate the CO2 from other gases mainly done from using **absorption technology**. This is characterized by using a liquid/solvent that selectively absorbs CO2 from a gas stream. Absorption processes can **be chemical absorption or physical absorption**. The chemical absorption capture technology was developed 75 years ago but has recently been adapted to treat flue gas streams. (Refuge et al., 2021)

Within the CCS (Carbon Capture and Storage) community, researchers recognize the existence of alternative capture solutions. They emphasize the importance of tailoring each solution to suit the specific context.
The working group have primarily looked at point sources in Denmark and Sweden, incorporating combustion facilities, where the concentration is sufficient to make capture feasible. This will consequently constitute the main focus onwards.



Microbial and algae systems leverage organisms to absorb and convert CO2 into biomass through photosynthesis.
Adsorption, which employs solid materials known as adsorbents to attract and capture CO2 molecules. The adsorbents can be regenerated for continuous use, making it a cyclic process.
Cryogenics takes a cooling approach. By lowering the temperature of flue gases to extremely low levels, CO2 condenses into a liquid form.
Absorption relies on liquid absorbents or solvents to capture CO2 from flue gases. Once absorbed, the CO2-laden solution can be processed to release the captured CO2 for storage or further use.
Membrane involves selectively permeable membranes that allow CO2 to pass through while blocking other gases, providing a separation mechanism for flue gases.
Amine scrubbing utilizes chemical solutions, known as amines, to absorb CO2. The amine-CO2 solution is then separated, and the amine is regenerated for reuse in the capture process.
In **oxyfuel combustion**, the traditional combustion process is modified by using oxygen instead of air. This results in a flue gas stream predominantly composed of CO2 and water vapor, simplifying the subsequent capture process.
Electrodialysis extract CO2 from seawater using electrodialysis technology. Ion-selective membranes facilitate the separation and concentration of CO2 ions from the ocean water.

(Refuge et al, 2021)

Figure 1: Overview of different capture technologies available today.
All capture technologies capture CO2 in its gaseous form.
The overview is peer-reviewed by CCUS experts; however, the list is not exhaustive.

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CO2 Supply

Estimating CO2 from Malmö and Copenhagen until 2035

Collaborative efforts to capture, transport and store CO2 – Sweden

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Formation of Carbon Clusters
Several regions in Europe have formed carbon clusters to explore and potentially leverage the collaboration potential between capturing, transporting and storing carbon dioxide. This is also the case in South Sweden.

CNetSS in Sweden
In South Sweden, the carbon cluster, CNetSS (Carbon Network South Sweden) has a goal to increase the potential for both reducing emissions and contribute with negative emissions. CNetSS wants to establish a sustainable, cost-efficient carbon dioxide infrastructure for transport from emission plants to final geological storage. By collaborating, the stakeholders aims to create a value chain for carbon capture and storage where the cost of the entire chain can be significantly reduced because of shared costs.

However, relatively long distances between combustion facilities introduces logistical and technical challenges for transporting and storing CO2

Figure 2: blue dots: CO2 emitters, red dots: port operators

CNetSS (Carbon Network South Sweden)

Major emitters in South Sweden with scheduled plans to capture CO2 in near future. Currently, they explore the possibilities of lowering infrastructure costs by collaborating and developing common infrastructures. CMP in Malmö is appointed as a node for interim carbon storage before shipment to final storage site.

Estimating CO_2 Supply in South Sweden

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By drawing on data provided by 6 CnetSS members, it is possible to estimate the CO_2 supply in South Sweden. The number is not indicative for the total amount of potential captured CO_2, but only for captured CO_2 from the 6 emitters as depicted in figure 3. Interviewed members of the CnetSS emphasize the possibility of connecting other emitters to future transportation infrastructure.

The potential captured CO_2 is expected to be on a very small scale the first operational years due to the few and immature capturing facilities in 2027 and 2028. Most combustion facilities are expected to be fully developed by 2030 capturing almost 1.6 MtCO_2/y. **The network expects in 2035 a peak of 1.7 MtCO_2/y to be captured. Approximately 1 million tons of CO_2 per year are expected to be captured in the Malmö-Helsingborg area**.

The capacity of the potential CO_2 Hub in Malmö mirrors the potential captured CO_2, but changes in quantity may happen over time as more CO_2-capturing stakeholders are likely to connect to the already planned infrastructure.

The potential captured CO_2 is determined by:

- CO_2 source; quality and quantity
- Capture technology
- Implementation scale
- Policy and economic viability
- Geographical considerations

Potential Captured CO_2 - CnetSS

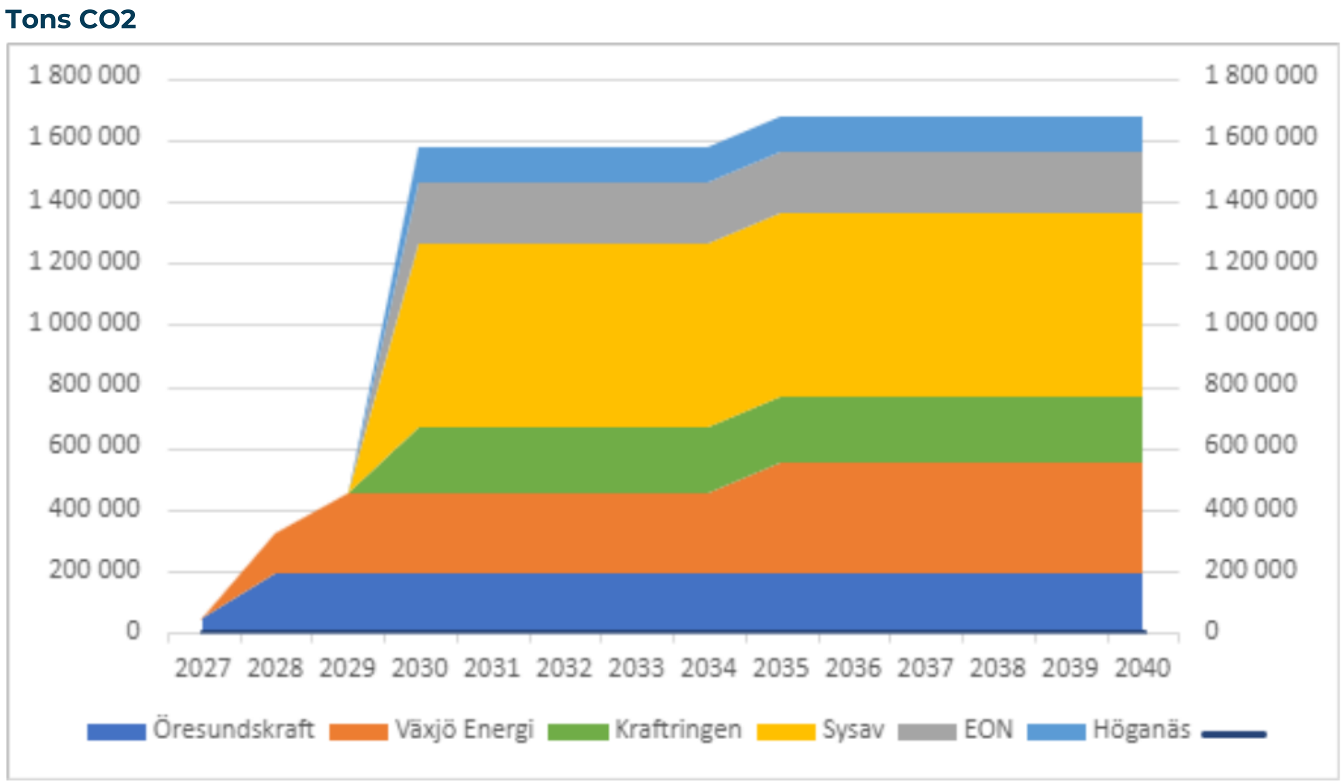

Figure 3: expected CO_2 supply from 6 major emitters in South Sweden

The combustion facility at Sysav is the biggest contributor of captured CO_2 with almost 23% of the total captured CO_2 in the future. 1.7 Mt$CO_2$7/y is a relatively small number compared to other regions and countries but still suitable for many re-utilization cases, but one could question if the first operational years would provide enough CO_2 to make such cases feasible, according to interviewed CCUS experts.

Why seasonal variations in capturing CO2?

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Monthly variations in captured CO2 - CnetSS

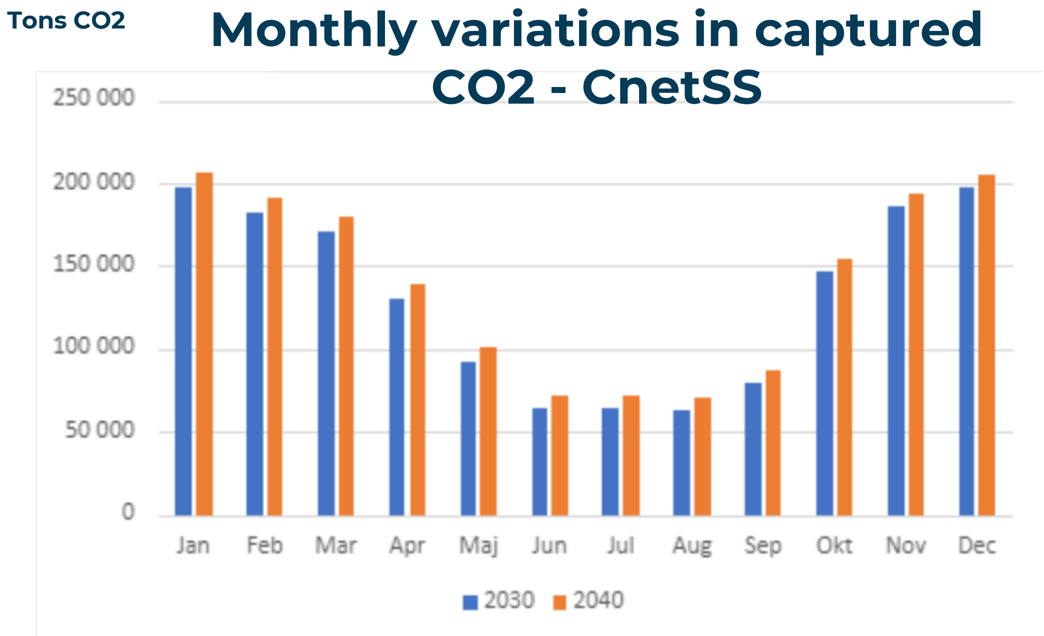

Figure 4: Expected CO2 supply per month (2030 & 2040)

With offset in the CNetSS, it is possible to estimate monthly CO2 supply in 2030 and 2040. The winter months have a higher supply compared to expected supply in summer months.
Figure 4 is not complete as it is expected more emitters connect to the not-yet-established infrastructure, however it represents most of the major emitters in South Sweden.

It has not been possible to get data on daily variations. Nonetheless, the daily variations could be an important element to assess for multiple re-use cases as the supply-side needs to be consistent and stable.

Seasonal variations in CO2 supply
During wintertime, there is an increased availability of CO2 due to the demand for district heating. The winter months also often coincide with heightened human energy activities and increased industrial production. In South Sweden, the expected peak variation between highest and lowest months is 140.000 tCO2/y equivalent to 8% of the total captured CO2 in year 2035.

No significant variation expected in the supply of CO2 between 2030 and 2040
In 2030 and 2040, almost all major emitters in the CnetSS have fully developed carbon capturing facilities, according to their schedules. The development corresponds to the monthly graphs presented to the left which shows little variation between 2030 and 2040 supply levels.

Do seasonal variations have implication for potential CO2 off-takers?
Understanding the predictability of CO2 supply is crucial. A stable and reliable supply is essential, especially in the context of re-utilization cases . If the supply is not dependable and consistent, it can have implications for off-takers who rely on CO2 as a resource. This is particularly pertinent for companies involved in e-fuel production, as they require a reliable CO2 supply to sustain their operations and ensure the efficiency of e-fuel production. However, project participants do not express concern about supply security at the present time. This could become relevant in the future, especially for biogenic CO2 explored on the next page.

Unique Biogenic CO2 Capture in Sweden

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Distinguishing between biogenic and fossil CO2
It is crucial to distinguish between biogenic CO2 and fossil CO2 for accurately assessing carbon footprints, developing effective climate change mitigation strategies, complying with regulations, and ensuring the sustainability of renewable energy and carbon capture technologies. South Sweden has a vast potential to capture biogenic CO2 compared to other European countries. The reason is Sweden's utilization of bioenergy or biomass for energy production and effective waste management practices. Figure 5 illustrates that almost 70% of the captured CO2 is biogenic. This starkly contrasts with figure 6, which depicts the average biogenic share for other European countries.

Fossil CO2: Fossil CO2 originates from the combustion of fossil fuels such as coal, oil, and natural gas. Fossil CO2 is a major contributor to anthropogenic climate change because it introduces additional carbon into the atmosphere

Biogenic CO2: Emissions that result from the natural carbon cycle, primarily the biological processes associated with living organisms. It is often regarded as carbon-neutral in the sense that the carbon emitted was recently taken from the atmosphere through natural processes.

Share of biogenic versus fossil CO2 – Southern Sweden

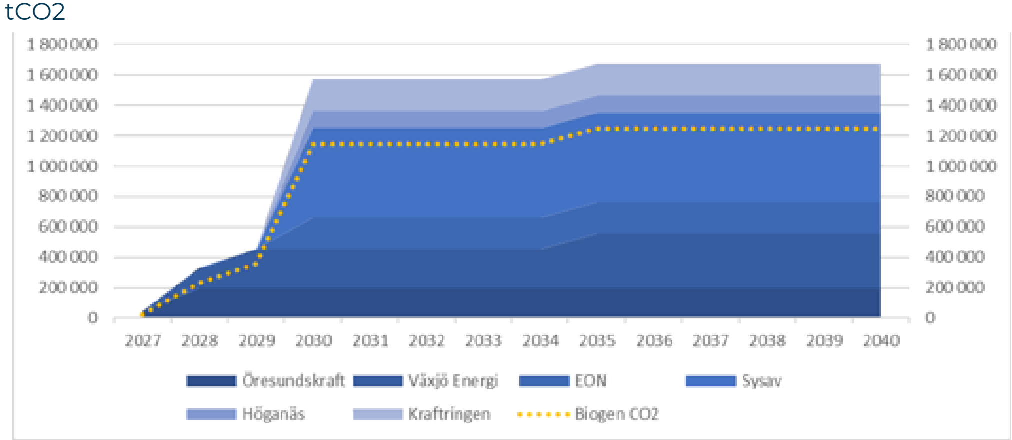

Figure 5: The share of **biogenic CO2** is **averaging 70%** of the total CO2 volumes captured in South Sweden.
Baseline: **6 major emitters in CnetSS**.

Source: CnetSS

Share of biogenic versus fossil CO2 – 8 European Countries

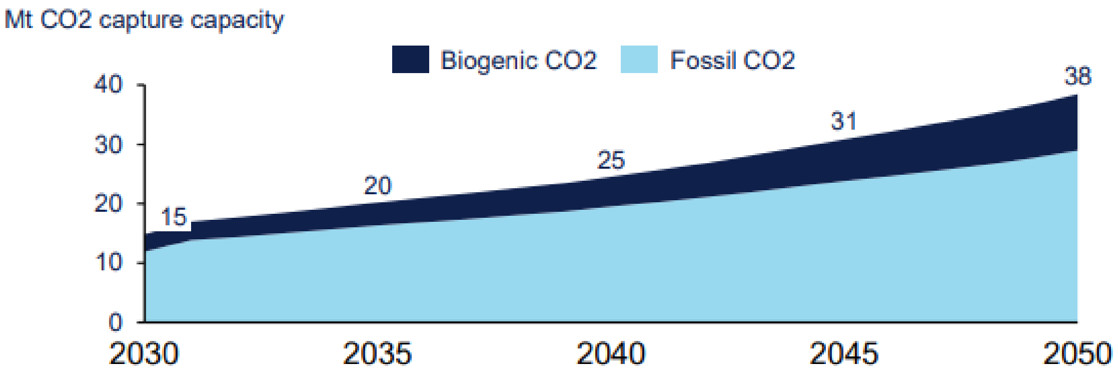

Figure 6: The share of **biogenic CO2** is **averaging 21%** of the total CO2 volumes captured.
Baseline: **Germany, Poland, Czechia, Lithuania, Latvia, Estonia, Finland and Sweden**

Source: DNV (2024)

Collaborative efforts to capture, transport and store CO2 – Denmark

Carbon Cluster in Greater Copenhagen
The Copenhagen metropolitan area presents an ideal setting for establishing carbon capture transport facilities, primarily due to the concentration of large energy companies in relatively close proximity. This proximity facilitates better opportunities for joint infrastructure development.

A carbon cluster, known as C4, has been formed by these large energy companies, akin to the Swedish CnetSS but with slightly higher capture capacity. **The C4 cluster aims to capture approximately 3 million tons of CO2 annually during peak years.** Amager Vestforbrænding is expected to contribute 450,000 tons of CO2 per year from 2030 onwards, slightly more than Sysav in Sweden. This 3 million ton target corresponds to approximately 15% of Denmark's total reduction target of 70% by 2030.

The parties involved in the C4 cluster are committed to exploring and, if feasible, realizing the vision of capturing and either storing or utilizing large amounts of CO2 within the Copenhagen metropolitan area.

However, despite ongoing collaboration discussions, the C4 network has yet to reach a consensus on the design of the infrastructure. While collaboration offers cost efficiencies, it also brings to light the individual needs and specific agendas of each stakeholder when developing new infrastructure.

C4 Cluster Network

Major emitters and logistic operators in Denmark with scheduled plans to capture, store and transport CO2 in near future

arc – alt med affald
argo
BIOFOS
CMP – COPENHAGEN MALMÖ PORT
CTR
HOFOR
VEKS – Grøn fjernvarme til dig
VESTFORBRÆNDING
Ørsted

Estimating CO2 supply in Denmark

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Larger pool of potential captured CO2 than Sweden
Denmark boasts a larger potential reservoir for captured CO2 compared to Sweden. While the majority of the captured CO2 still originates from non-biogenic sources, Denmark's future capacity for captured CO2 surpasses that of Sweden. By 2035, Denmark anticipates being capable of capturing nearly 1.3 million tons more CO2 than Sweden.

Exploring the opportunity of importing CO2
Presently, Denmark is exploring the possibility of importing CO2. Leveraging its favorable storage conditions, both onshore and offshore, Denmark could store a significantly larger amount of CO2 than it emits. This presents collaborative opportunities wherein optimal storage conditions can be utilized, allowing for the profitable import of CO2 from other European countries.

Still no consensus yet on transportation and storage methods
However, accurately estimating the potential for captured and imported CO2 poses challenges due to the necessity for infrastructure supporting transportation to final storage sites. Achieving consensus and commitments for the development of CO2 transport infrastructure is a multifaceted endeavor, demanding collaboration and engagement from various stakeholders across the value chain. Presently, the C4 network has yet to decide whether captured CO2 should be transported via ship, pipeline, or truck to a final storage site that remains unidentified.

Potential captured MtCO2 by 2030

Sources	Scenario 1	Scenario 2	Scenario 3
Captured in Copenhagen	1,5	2,0	2,0
Captured from rest of Sjaelland	0,0	0,5	1,0
Import	0,0	0,0	2,0
Total CO2 2030	1,5	2,5	5,0
Destinations			
Storage Havnsø	0,0	0,0	4,0
Ship Transport	1,5	2,5	1,0
Ptx	Først efter 2030		
Total CO2 2030	1,5	2,5	5,0

7:

Figure 7: Potential captured, imported and stored CO2 estimated in 3 different scenarios.
Source: C4 (2023)

According to the C4 Cluster (2023), the potential for economically viable capture is estimated to be approximately **3 million tons of CO2 per year in 2030,** assuming favorable **conditions**. Additionally, there is potential for **the import of around 4.5 million tons of CO2 per year in 2030**, which could theoretically grow to 20 million tons of CO2 per year in 2050, given the existence of a local CO2 storage linked to the CO2 infrastructure, such as the port in Havnsø. (C4, 2023, p. 29)

Seasonal variations balanced by import projections

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Quarterly CO2 emissions– C4 Cluster

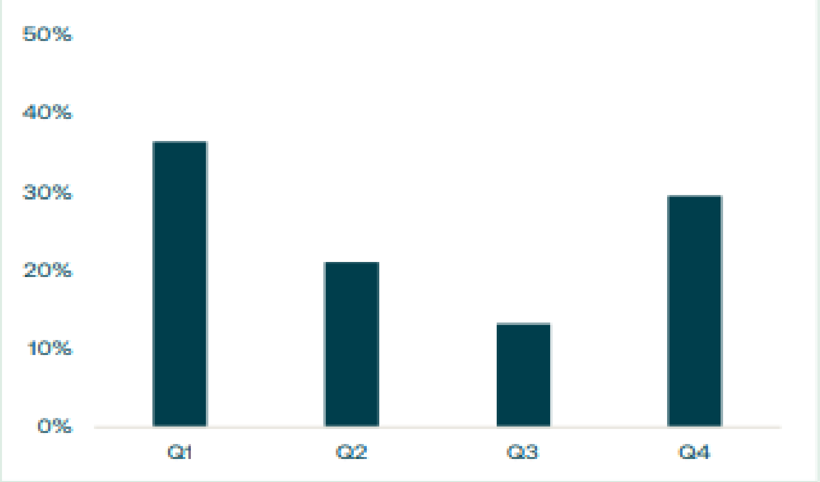

Figure 8: Quarterly fluctuations in CO2 emissions, shown as a share of total annual emissions.
Source: C4 (2023)

Similar seasonal patterns as in South Sweden
Denmark would experience similar seasonal CO2 capture variations as Sweden, with its relatively higher emissions in Q1 compared to summer months (Q2 and Q3). Only 15% of the yearly emissions from the C4 network is emitted in Q3 contrasting almost 40% in Q1. Therefore, Denmark would need to adjust its CO2 transportation strategies to align with these seasonal fluctuations in emissions.

How much biogenic CO2 comes from Greater Copenhagen?
More than 50% of the total CO2 captured is expected to come from biogenic sources in Greater Copenhagen (70% in South Sweden.

The predominance of CO2 capture from biogenic sources in Denmark can be attributed to the country's significant focus on sustainability and renewable energy sources.
Denmark has made substantial investments in renewable energy, including biomass and bioenergy technologies. These initiatives aim to transition away from fossil fuels, reduce carbon emissions, and promote a more environmentally friendly energy sector.
As a result, a substantial portion of the expected CO2 capture comes from biogenic sources due to the emphasis on harnessing energy from organic materials.

Import balancing the expected seasonal variations
Another important aspect and potential x-factor to include when projecting the CO2 supply from Greater Copenhagen is the aspect of import of CO2 due to favorable storage conditions in Denmark. The import of CO2 could potentially balance the fluctuations in CO2 hence ensuring a stable supply of CO2.
This important aspect is elaborated and included in the supply analysis on the following page.

Denmark as CO2 importing country?

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Importing CO2 involves bringing carbon dioxide from external sources to Denmark. The initiative holds significant promise for several reasons. Preliminary assessments suggest that Denmark has the potential to store a considerable amount of imported CO2. Also, Denmark's geographical location and connectivity makes the country a feasible final storage destination. Later in the report, a storage analysis underscores the significant capacity Denmark possesses for storing CO2 in the near future. The findings indicate that Denmark has the potential to store a far greater amount of CO2 than it currently emits into the atmosphere.

The import ratio is contingent on future infrastructure developments

However, no consensus has been reached between involved stakeholders on where to built a CO2 infrastructure supporting the transportation. The uncertainty in import ratios plays an important role behind the lacking consensus on infrastructure developments. Below, is two different assessments of import ratios presented, both contributing to discrepancy of import ratios. An important point to highlight is that, with adequate infrastructure development, Copenhagen possesses an excess supply of captured CO2.

Import method	Current pathway potential [MTPA]	Net zero pathway potential [MTPA]	Predominant origin countries
Vessel transport	7.4	31	Finland, Sweden, Estonia, Latvia, Lithuania
Pipeline transport	16.5	46	Poland, Germany, Czechia

Figure 9: Expected potential for importing CO2 (DNV)

Note: The table above represents numbers covering Denmark in general, and not only Greater Copenhagen. Notice that the presented volumes are the volumes that are identified as the most feasible, both in terms of distance and in terms of sector origin

.

Source: DNV (2024)

MtCO2/year	2025	2030	2050
Import Sweden	0	1	5
Import Germany	0	2	8
Import Finland	0,3	0,5	3
Import Poland	0	1	4
Total Import	0,3	4,5	20

Figure 10: Expected potential for importing CO2 if an attractive price point is established (C4).

In a study, C4 concludes the import of CO2 is expected to be significant from 2030 and onwards. In 2030 it is estimated that Greater Copenhagen could import 4,5 MCO2/ year from 4 different countries.

Source: C4 (2023)

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Demand

Estimating future CO_2 demand based on feasible re-utilization cases

Estimating demand created from re-utilization cases

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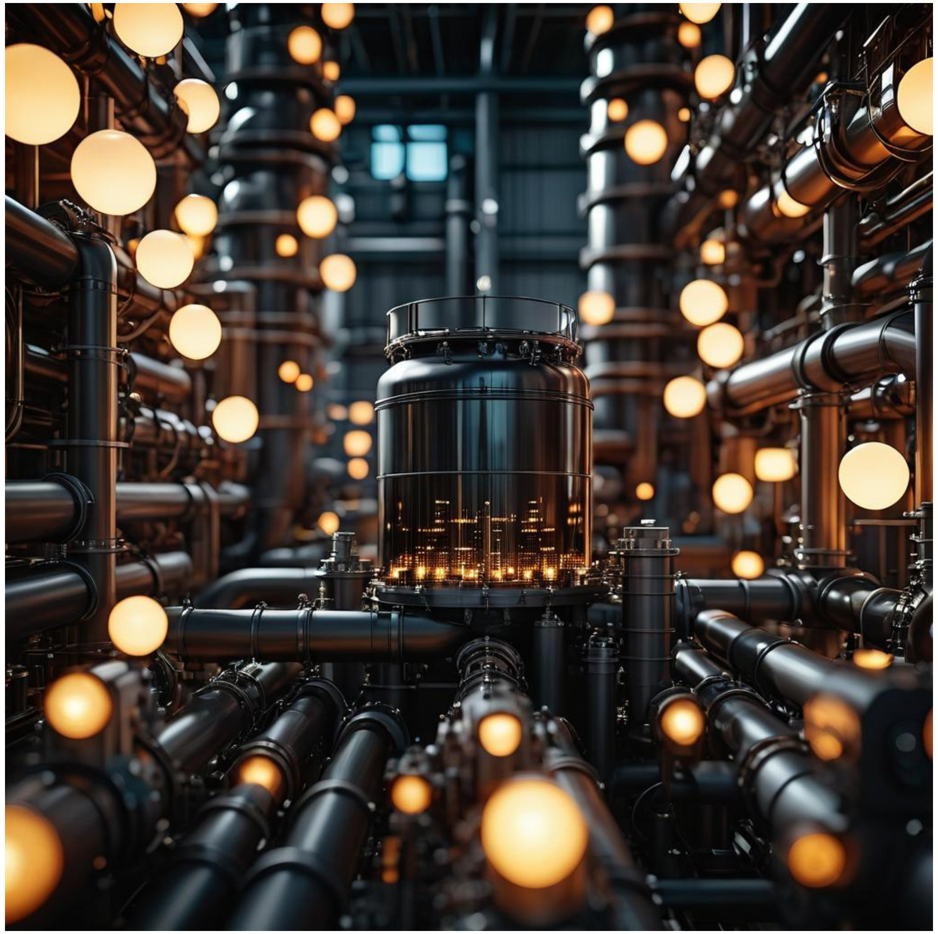
Reutilization; a small fraction of current emissions.
In the anticipated trajectory for 2025, it is projected that only 272 million metric tons of carbon dioxide (MtCO2) will be reutilized globally. To provide context, the combined carbon dioxide emissions stemming from fossil fuel consumption and industrial activities amounted to 37.15 billion metric tons (GtCO_2) in 2022 (Statista, 2023). Therefore, the figure of 272 MtCO2/year represents a small fraction, approximately 0.000732%, of the total annual emissions worldwide (IEA, 2019). It is noteworthy that not all emitted CO2 is feasibly to capture; nevertheless, it underscores the fact that the current demand for reutilized carbon dioxide constitutes a marginal proportion of the global emissions landscape



Numerous reuse opportunities exist, yet they face several challenges, as outlined by interviewed experts in Carbon Capture, Utilization, and Storage (CCUS):

- Inefficiencies in energy conversion, where power generation is utilized to produce power.
- Technological immaturity hindering progress.
- Prevailing focus on capturing CO2 to mitigate emissions rather than prioritizing its reuse, relegating reuse initiatives to a secondary position.
- Lack of proactive initiatives aimed specifically at CO2 reutilization, with cost-efficient storage solutions often taking precedence.
- Dominant emphasis on CO2 reduction over its reuse within the current paradigm, driven by international climate policies predominantly targeting greenhouse gas (GHG) emission reductions through Carbon Capture and Storage (CCS) initiatives.

Nevertheless, certain stakeholders are actively exploring the market potential of reutilizing captured CO2. This exploration is accompanied by a growing interest in investments from global multinational corporations, emphasized in subsequent discussions.

1 GtCO2 = 1.000.000.000 MtCO2

Large corporations are increasingly investing in re-utilization initiatives, signaling a potential shift towards a more circular future

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The seven-year-project has been awarded with a grant of 630 million DKK (84.7 million EUR) and will have a unique interdisciplinary approach to develop novel innovative ideas and early technology platforms to solve the greenhouse gas-based climate crisis
Source: (Ritzau, 2022)

Captura raises US$21.5M, with investments from Maersk Growth, Eni Next and EDP
Source: (Captura, 2024)

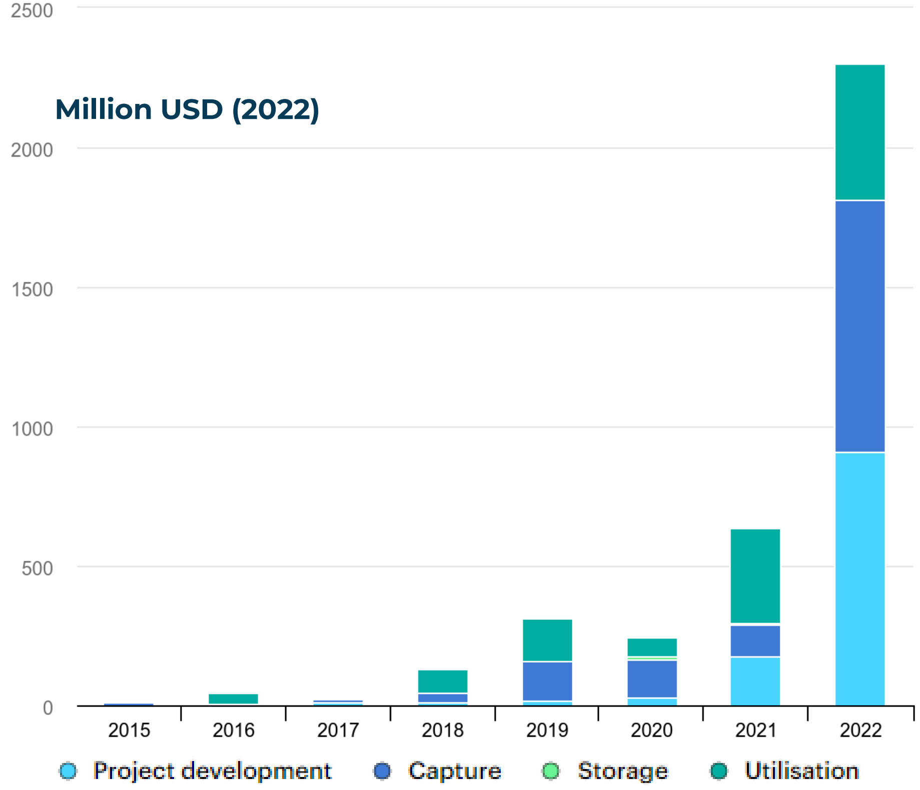

Figure 11: Annual venture capital investment in CCUS projects and companies, 2015-2022 (IEA, 2022)

The increasing interest in CO2 conversion technologies is reflected in the growing amount of private and public funding that has been channeled to companies in the re-utilization field. Corporate goals and quotas for low-emission fuels and materials are boosting CO2 use for sustainable aviation fuels and building materials.

novo nordisk foundation

BILL & MELINDA GATES foundation

DKK 200 million (approx. US$29 million) over a two-year period for a research and development (R&D) project aimed at creating a sustainable source of protein for human food derived from CO2.
Source: (Novo Nordisk Fonden, 2023)

Egypt, Maersk's C2X sign agreement worth up to $3 bln for production of green fuel - statement
Source: (Reuters, 2023)

Exploring Dominant Reutilization Cases: A Current Overview

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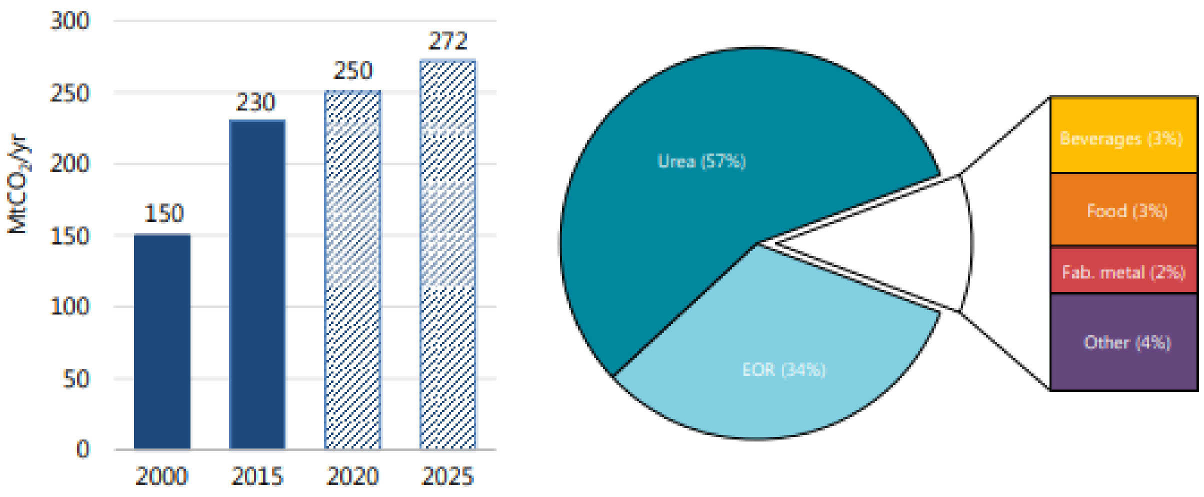

Note: Projections for future global CO_2 demand are based on an average year-on-year growth rate of 1.7%.

Sources: Analysis based on ETC (2018), *Carbon Capture in a Zero-Carbon Economy*; IHS Markit (2018), *Chemical Economics Handbool Carbon Dioxide*; US EPA (2018), *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2016*.

Global consumption of CO_2 is estimated to be 230 Mt/yr and expected to grow steadily over the coming years; consumption is mainly driven by EOR and on-site demand for urea production.

Figure 12: Growth in global demand of CO2 over the years (left); breakdown of demand in 2015 (right).

*Urea: fertilizer for agriculture

Current reutilization cases: Global overview

In 2015, around 230 million tons (Mt) of CO2 were used each year (figure 12). The largest consumer was the fertilizer industry, around 130 MtCO2 per year was used in urea* manufacturing, followed by the oil sector, with a consumption of 70 to 80 MtCO2 for enhanced oil recovery (EOR) (IEA, 2019). CO2 is also widely used in food and beverage production, the fabrication of metal, cooling, fire suppression and in greenhouses to stimulate plant growth.

New pathways for CO2 are generating global interest

The range of potential CO2 utilization cases is very large and includes direct use, by which CO2 is not chemically altered and the use of CO2 by transformation (via multiple chemical and biological processes) to fuels, chemicals and building materials.

Although most conversion pathways are highly energy-intensive and still in their infancy, they are attracting growing interest and support from governments, industry and investors.

Putting Reutilization Cases into Perspective

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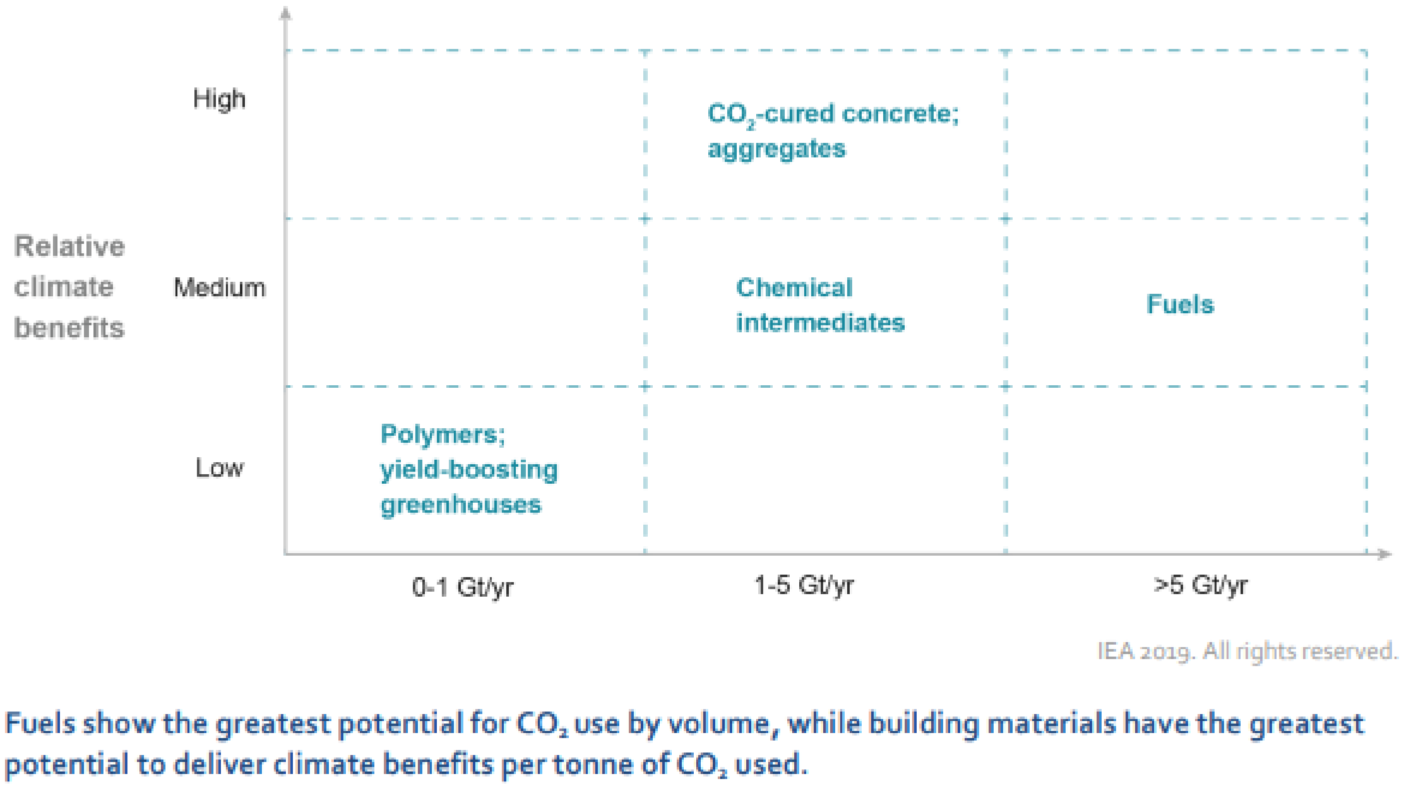

Figure 13: Theoretical potential and climate benefits of CO2-derived products and services

Unveiling the Potential of Carbon Utilization

- Despite existing utilization methods, there remains considerable untapped potential, as indicated by interviewed experts.
- Economic and energy costs, particularly evident in e-fuels, present significant barriers to widespread adoption.
- The prevailing paradigm prioritizes CO2 storage over utilization, shifting the focus from Carbon Capture, Utilization, and Storage (CCUS) to primarily Carbon Capture and Storage (CCS).

CO2 is expected to be utilized on a large scale for the production of various fuels.

- Methane
- Methanol
- Gasoline
- Biofuel
- SAF (aviation fuels)

The process involves using the CO2 in combination with hydrogen, which is highly energy-intensive to produce, and results in a carbon-containing fuel that is easier to handle and use than pure hydrogen.

Participants in the project, along with CCUS experts interviewed, emphasize the critical role of electricity as a limiting factor in reutilization cases, particularly in the production of e-fuels. This topic will be further discussed on the following slide.

Electricity poses a constraint on the production of future fuels.

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The production of e-fuels requires a significant amount of energy. For example, to produce 100,000 tons of e-methanol (with hydrogen sourced from a p-t-x facility), the p-t-x facility consumes approximately 1200 GWh annually, equivalent to three percent of Denmark's total electricity consumption*. The example highlights current CO2 utilization technology as relatively high energy-intensive processes.

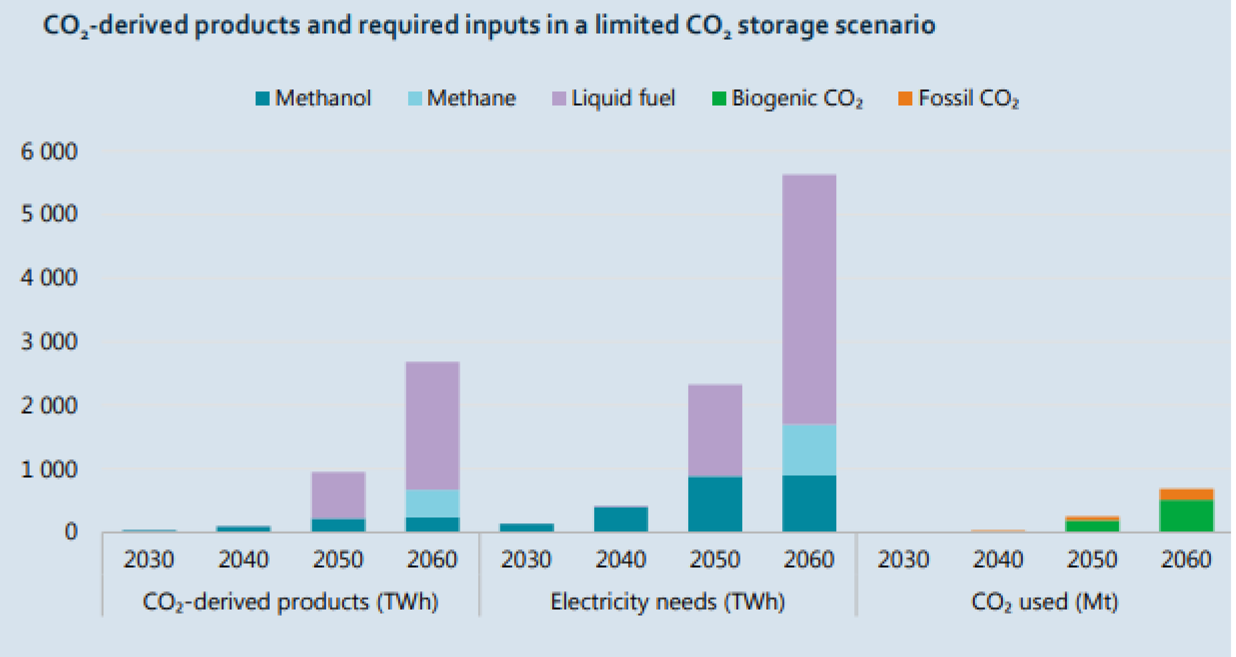

Figure 14: CO2-derived products and required inputs in a limited CO2 storage scenario. Source: IEA, 2019

*European Energy bygger PtX anlæg i Nakskov| Business Lolland-Falster (businesslf.dk)

Electricity as the limiting factor

Limited CO2 storage availability could result in nearly six-fold increase in electrolysis-based methanol according to figure 14 made by the International Energy Agency (2019). But favorable storage options exist both onshore and off-shore in territory of Denmark making the figure insignificant to Oresund Region.

However, the figure can be used to emphasize the need for enormous amounts of electricity to produce e-methanol, methane and liquid fuels.

Figure 14 shows that CO2-derived products could potentially produce 240 TWh (44 Gt) of methanol and over 2 400 TWh (8.7 EJ) of fuels in 2060, requiring 5 600 TWh of electricity generation and 684 MtCO2.

The figure raises important questions related to fuels production:

- Is the Oresund Region able to produce and/or import enough green electricity to supply fuel regional fuel production?
- Is it feasible to produce fuels in regions with high electricity prices?
- Are there alternative utilization technologies or processes that could alleviate the strain on electricity generation?

Putting Danish Power-to-X Projected Demand into Perspective

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The table below outlines Power-to-X projects currently operational or under discussion in Denmark. The collective CO2 demand from these projects is projected to reach approximately 0.3 million tons per annum (MTPA) by 2030 and around 0.6 MTPA by 2035. To underscore the significance of this CO2 demand, the figure of 0.6 MTPA equates to 20% of Denmark's anticipated CO2 capture in 2035. (DNV, 2024)

Area	Company	Feedstock	Operational status	Anticipated CO2 demand (Tpa)	Startup year	Fuel category	Product
Aabenraa	European Energy	Electrolysis and CO2 from Biogas Plants	In operation	43,945	2023	E-fuel	E-methanol
Holstebro	ReIntegrate	CO2 from biogas plant and H2 from water electrolysis	In operation	13,733	2023	E-fuel	E-methanol
Aalborg	European Energy and Port of Aalborg	Electrolysis	Under discussion	102,996	2025	E-fuel	E-methanol
Hanstholm	European Energy and Port of Hanstholm	CO2 and H2 from water electrolysis	Under discussion	43,945	2025	E-fuel	E-methanol
Copenhagen/ Kalundborg*	Ørsted, SAS, Copenhagen Airports, AP Moller – Maersk, DFDS and DSV, with Nel, Haldor Topsøe and Everfuel**	CO2 and H2 from water electrolysis	Under discussion	69,000	2025	E-fuel	E-methanol
				137,000	2027		
				378,000	2035		
Aalborg	CiP	CO2 and H2 from water electrolysis	Under discussion	180,000	2027	E-fuel	E-methanol

In another study, Brintbranchen, the primary organization for hydrogen and PtX in Denmark, anticipates the production of approximately 0.7 million tons (Mt) of e-methanol and 0.2 Mt of e-kerosene in Denmark by 2030. This translates to a CO2 demand of approximately 1.4 million tons per annum (MTPA) by 2030*.

Anticipated demand falls well short of surpassing projected supply.
The table from DNV (2024) and the study conducted by Brintbranchen offering two differing estimations of the potential CO2 demand within a Danish context, highlights that the demand falls significantly short of exceeding the expected CO2 supply.
However, what if other re-use cases develop and regulatory changes alter demand dynamics? This will be explored in the next section.

*https://brintbranchen.dk/brintprojekter-i-danmark/

Factors influencing re-use cases

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Electricity prices and capacity
The cost of electricity, which is often a significant component of CCUS projects, can impact the economic viability of re-use cases. Fluctuations in electricity prices can affect the operating costs and overall competitiveness of CCUS technologies for re-use purposes.

Available Biogenic CO2 Supply
The availability of biogenic sources of CO2, such as emissions from biomass or waste processing facilities, can impact the overall supply of CO2 for re-use purposes. The accessibility and sustainability of these sources play a crucial role in determining the feasibility and scalability of CCUS projects.

CO2 market price
The demand for products derived from captured carbon dioxide, such as fuels, chemicals, and materials, plays a key role in driving investment and innovation in re-use cases

Supporting infrastructure
The availability and accessibility of infrastructure for transporting, storing, and utilizing captured carbon dioxide can determine the feasibility and scalability of re-use projects.

Technological development
The readiness and effectiveness of available technologies for capturing, utilizing, and storing carbon dioxide play a crucial role in influencing re-use cases

ETS credits
The availability and pricing of Emissions Trading System (ETS) credits can affect the economics of CCUS projects. ETS credits provide financial incentives for reducing emissions, and the ability to generate credits through carbon capture and storage activities can influence investment decisions in re-use cases.

Supply Chain Integration
The integration of CCUS technologies into existing supply chains for fuels, chemicals, and materials can influence demand dynamics. Collaboration and partnerships across industries to streamline supply chain integration can enhance the attractiveness and feasibility of re-use cases

Regulatory framework
The presence of supportive policies, incentives, and regulations can significantly impact the development and deployment of CCUS technologies for re-use purposes.
For example, EU's new regulation of Sustainable Aviation Fuels*

EU Council adopts new renewable energy rules and rules for promotion of sustainable aviation fuels under Fit for 55 | EY - Global

To gauge the potential value of CO2, it's crucial to delve into the factors driving pricing. The analysis of these pricing drivers is part of the future work undertaken by project partners at Ocean Valley.

Exploring Other Viable Utilization Opportunities

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The Oresund Region stands at the forefront of innovation and sustainability, poised to explore new frontiers in carbon utilization. With a unique combination of factors that make it an ideal hub for such endeavors, the region presents compelling opportunities for leveraging carbon capture and utilization (CCUS) technologies

Why is utilization interesting in the Oresund Region:

- High biogenic CO2 share compared to other regions (70% in South Sweden, 50% in Greater Copenhagen)
- Potentially, a supporting transport infrastructure creating free flows and cost-effective transportation.
- Strong government support and regional commitment to sustainability and innovation
- Availability of skilled workforce and research institutions specializing in carbon capture and utilization technologies, fostering innovation and collaboration in the region.
- Strategic location with access to international markets, offering opportunities for exporting carbon-derived products and driving economic growth.
- Potential for collaboration with neighboring regions and countries on cross-border utilization projects, leveraging synergies and sharing resources to maximize impact

Capturing CO2 from Oceans - Captura

Through Direct Ocean Capture, Capturas removes CO2 from the upper ocean, enhancing the ocean's capacity to draw more carbon from the air. Once captured, the CO2 is safely and securely stored, via solutions like geologic sequestration, so it can no longer contribute to climate change. Once excess carbon is removed from the ocean, it can be put toward a number of sustainable uses. In addition to storage, captured CO2 can be turned into sustainable fuel to power existing vehicles. For hard-to-decarbonize transport sectors such as aviation and shipping, this provides a drop-in ready alternative to fossil fuels, with a high energy density and low carbon footprint.
https://capturacorp.com/solutions/

Utilizing CO2 to proteins: Novo Nordisk & Bill Gates Foundation

Companies and university researchers will create a sustainable source of proteins for human food derived from CO2. The aim is to help fight the rising global problems with food insecurity and greenhouse-gas emissions from agriculture. With this aim in sight, the Bill & Melinda Gates Foundation and the Novo Nordisk Foundation are funding a new consortium that will utilise CO2 to produce proteins for human food. By using biological and electrochemical processes, the consortium partners will process CO2 and turn it into acetate, which is vinegar – a well-known substance already present in the metabolism of the microorganisms used for fermentation. The acetate can then be used to produce proteins that can be used directly in food for humans.

CO2 as a sustainable raw material in our future food production - Novo Nordisk Fonden

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Captura (2024) Captura raises US$21.5M, with investments from Maersk Growth, Eni Next and EDP - Captura (capturacorp.com)

(Novo Nordisk Fonden, 2023) CO2 as a sustainable raw material in our future food production - Novo Nordisk Fonden

(Reuters, 2023) Egypt, Maersk's C2X sign agreement worth up to $3 bln for production of green fuel - statement | Reuters

Interviews

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DTU, Philip Fosbøll
Danish Technological Institute, Jan Boyesen
Green Power Denmark, Mathilde Sehested
CMP, Torben Lind
Öresundskraft, Maria Möller
DecarbonICE, Henrik Madsen
Carbon Cuts, Steffen Jacobsen
CORC, Stephanie Kristiansen
DFDS, Nibirh Mandal & Nana Thit Hemmingsen
Uniper, Ola Soler
Sysav, Magnus Pettersson
Växjo, Julia Ahlrot

Many thanks to all project participants for your valuable contributions and fruitful discussions during our meetings

DFDS e·on EY Maritime Research Alliance CMP COPENHAGEN MALMÖ PORT

Appendix

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Final Storage

An analysis of storage options in Northern Europe

CO2 Storage

The imperative to store CO2 lies in its potential to achieve negative emissions and prevent further emissions from point sources. National climate policies play a pivotal role in determining the scale of CO2 capture and storage efforts. Presently, significant quantities of CO2 are earmarked for storage, whether offshore, nearshore, or onshore. However, the infrastructure required for storage, including the transportation costs associated with moving CO2 to storage sites, poses a significant challenge. Consensus on storage solutions remains elusive on both sides of the Oresund. While storing CO2 is generally more cost-effective than reusing it, the establishment of storage sites in Europe is still in its infancy, with capacities lagging far behind anticipated storage needs.

In the following sections, we delve into the planned storage locations, projected volumes, and practical implementation strategies for CO2 storage.

CO2 Storage Analysis (DK)

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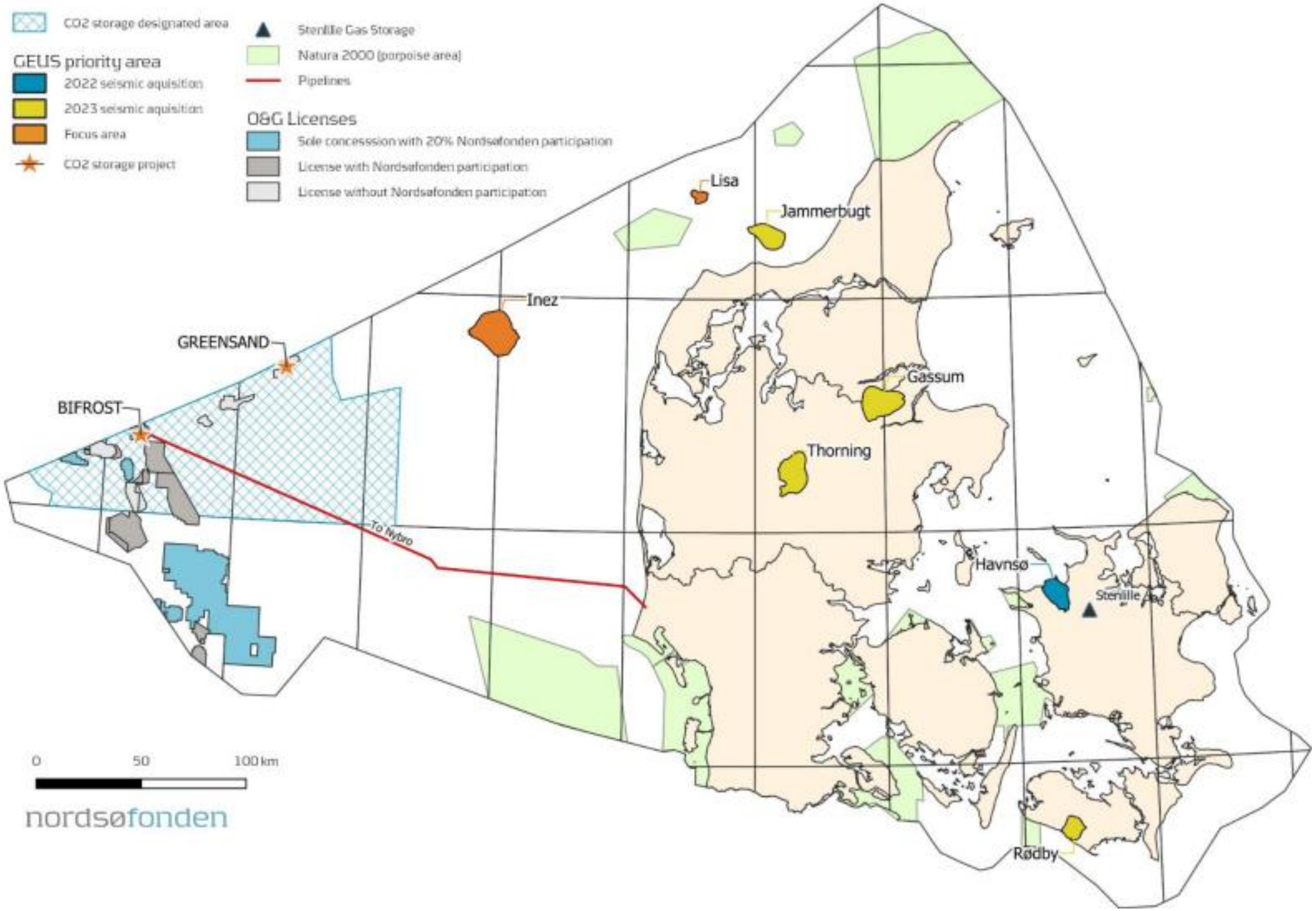

Research indicates that Denmark possesses significant storage potential due to favorable underground characteristics. Additionally, Danish stakeholders prioritize storage due to the potential for importing revenue streams.

Potential storage sites include onshore, nearshore and off-shore sites.

Havnsø*
Stenlille*
Rødby*
Thorning*
Gassum*
Bifrost*
Greensand*

*Only **exploration licenses** awarded in given areas.

Overview of Danish CO2 Storage Sites

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Field name	Onshore/ offshore?	Project	Status/maturity	Licensing	Planned availability
Stenlille	onshore	Stenlille demo	EIA expected finished end of 2023* Denmark's first onshore CO2 storage facility in Stenlille; goal to be operational by 1 April 2026.	Tendering planned	Aim contract signed dec 2023
Nini	offshore	Greensand	Under development	Licensed 2023	Operational from around 2025
Siri	offshore	Greensand	Under development		
Harald	offshore	Bifrost		Licensed 2023	
Havnsø***	onshore	n/a	"large and promising. Not drilled"; EIA (Environmental Impact Assessment) expected by end 2023*	Tendering planned	Q2-Q3 2024
Gassum***	onshore	n/a	"could be developed as storage option" EIA expected finished end of 2023*	Tendering planned	Q2-Q3 2024 project start**
Paarup / Thorning***	onshore	n/a	"could be developed as storage option"; EIA result expected end 2023	Tendering planned	Q2-Q3 2024 project start**
Vedsted	onshore	n/a	"mature for further development"		
Rødby	onshore	n/a	EIA expected finished end of 2023*	Tendering planned	Q2-Q3 2024 project start**
Inez***	offshore	n/a	EIA expected finished end of 2023*	Tendering planned	Q2-Q3 2024 project start**
Lisa***	nearshore	n/a	EIA expected finished end of 2023*	Tendering planned	Q2-Q3 2024 project start**
Jammerbugt***	nearshore	n/a	EIA expected finished end of 2023*	Tendering planned	Q2-Q3 2024 project start**
Hanstholm	nearshore	n/a	Status unknown		
Voldum	onshore	n/a	"could be developed as storage option"		

The diagram provides an overview of potential carbon storage sites within Denmark's territory. Some sites are already in the development phase, while others are undergoing environmental impact assessments. The first onshore project is anticipated to become operational by April 2026.

*First tender permit round for on shore and near shore storage sites expected to take place soon after EIA has ended.

**Timeline for sites on hearing: Q1 2024: tenders released for exploration; Q2 2024: Application review; Q2-Q3 2024: Licenses assigned. Projects can start up.

CO2 Storage Analysis - Scenario Case by DNV, 2024

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Introducing the DNV Scenario Study, "Denmark as a European Carbon Hub (2024) is particularly relevant as it provides key assumptions regarding storage capacity and injection ratios specific to the Danish context. The study underscores Denmark's unique position as a storage country with significant import opportunities. The 3 different scenarios are elaborated below.

In the scenario "**Each on their own**" it is assumed that only the onshore storage sites Havnsø and Gassum will be developed. These sites have had the most attention from different feasibility studies and is therefore assumed to be the first sites to be developed. For these storage sites to be developed, it will require agreements with several emitters in order to deliver a sufficient level of CO2. The investment costs and risks in developing a storage site are very high, and hence only two onshore locations are included in the scenario.

In the scenario "**Build and they will join**" four onshore locations are developed. As described in our methodology on storage sites, due to uncertainties pertaining to the size of storage capacities and injection rates, we distinguish between a case with a low and a high case of injection rates that is applied in the "current pathway" and "net zero pathway" scenarios, respectively.

The table to the right gives an overview of onshore and offshore injection rates assumed for the scenarios in this study. At most, 48 MTPA CO2 could be stored in Danish onshore and offshore storage sites.

As explained in the previous chapter, there are large uncertainties related to the storage capacities and injection estimates.

MTPA	Each on their own	Build and they will join Low injection rates	Build and they will join High injection rates
Onshore sites / Nearshore sites			
Gassum	3	3	4.5
Thorning	Not being developed	2	3
Hanstholm (NW Jutland)	Not being developed	8	12
Havnsø	3	3	4.5
Offshore sites			
Greensand	8	8	8
Bifrost	5	10	16
Total	**19**	**34**	**48**

The technical storage capacity depends on the actual properties of the aquifer, such as porosity, permeability, connectivity and physical size. However, the DNV (2024) study has made calculations on how much CO2 the different storage sites in Denmark could contain. These numbers outnumbers the total amount of captured CO2 in Denmark significant.

	GEUS Storage capacity P90 value [MT]	GEUS Storage capacity P50 value [MT]
Gassum	412	574
Thorning	202	290
Hanstholm (NW Jutland)	927	1293
Havnsø	204	294

CO2 Storage Analysis
- Northern Lights (Norway)

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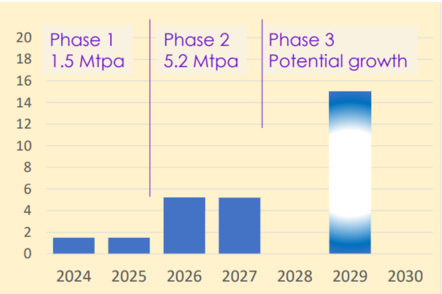
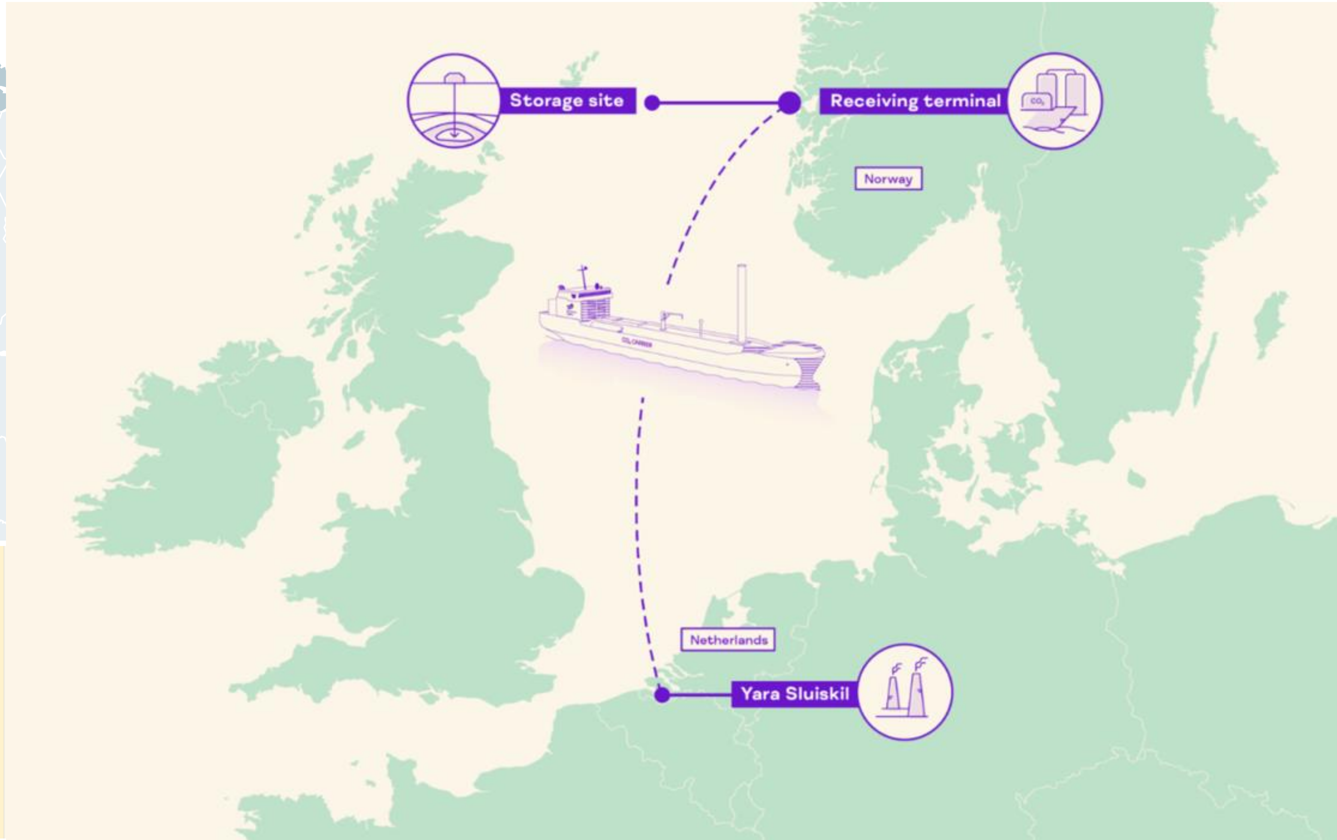
Additional and more established storage options are available, with various European projects also contributing to market development. This underscores the substantial demand within the industry to sequester CO2 and enhance sustainability. Norway, particularly through the Project Northern Lights, exemplifies the evolving storage market.





Northern Lights has cutting-edge technology already capable of receiving CO2 and is expected to be operational as early as Q1 2024, capable of handling significant quantities. By 2024, the facility is anticipated to be fully operational, with the capacity to store up to 1.5 million tons of CO2 annually.
By 2026, this capacity is projected to increase to 5.2 million tons of CO2 per year. Further expansion is anticipated by 2029, with the facility expected to handle up to 15 million tons of CO2 annually.

CO2 Storage Analysis (Where) - Sweden

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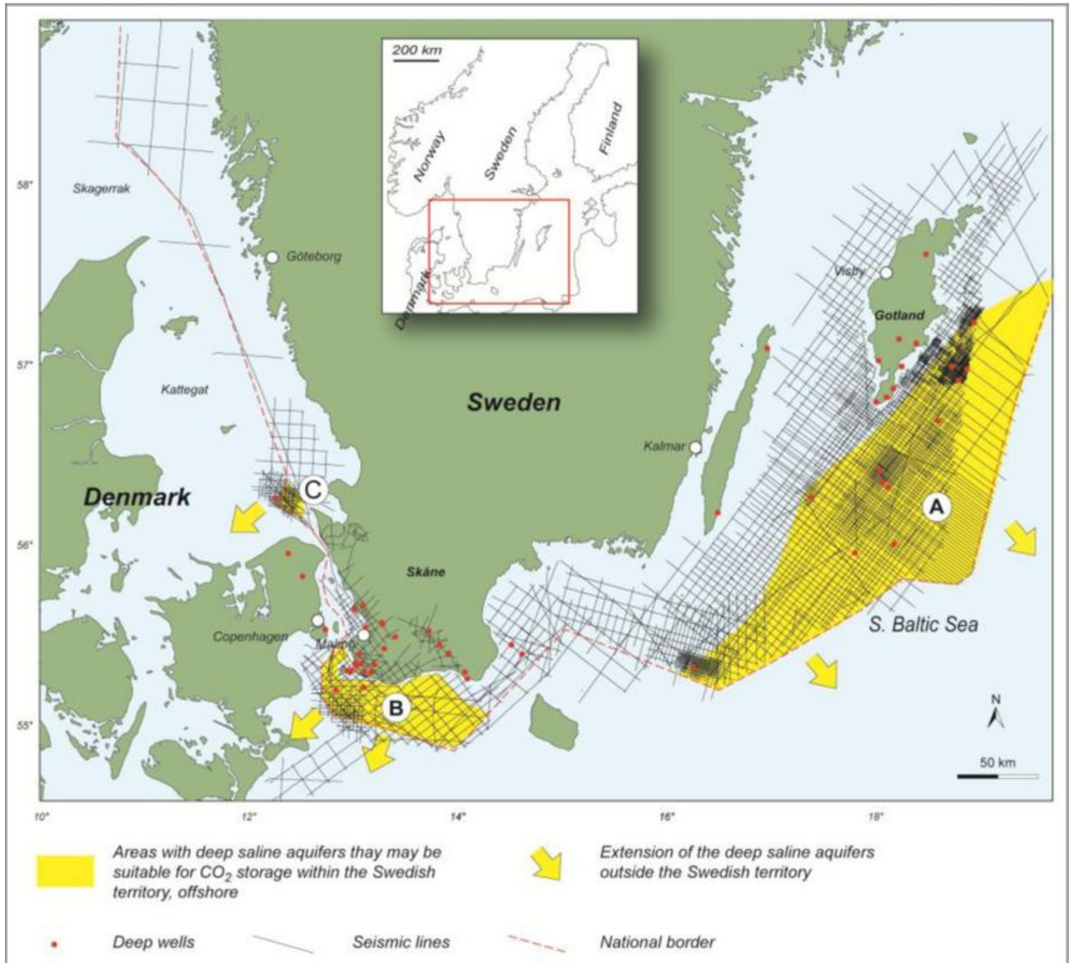

The Swedish perspective on CO2 storage involves a strategic approach to address the costly process of exploring new sites for carbon sequestration, particularly in light of the limited presence of the oil and gas industry within the country. Despite the relatively unexplored potential in the Baltic region, Sweden currently lacks a developed plan for CO2 storage within its territory. Instead, the focus lies on exporting CO2 abroad, with potential destinations including projects like Northern Lights, onshore sites in Denmark, or offshore locations in the North Sea.

CO2 Storage Analysis

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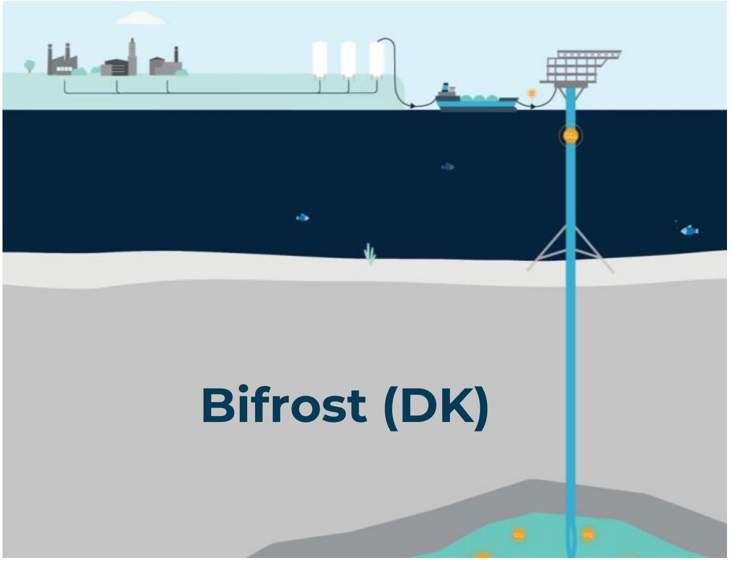
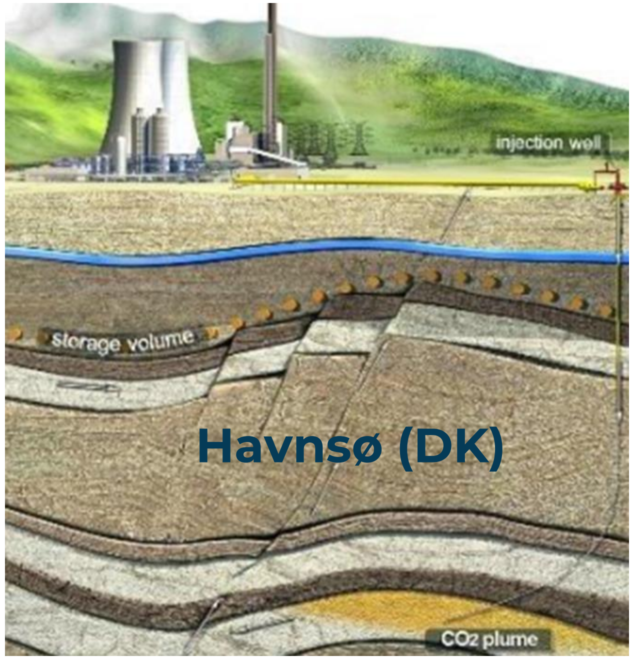
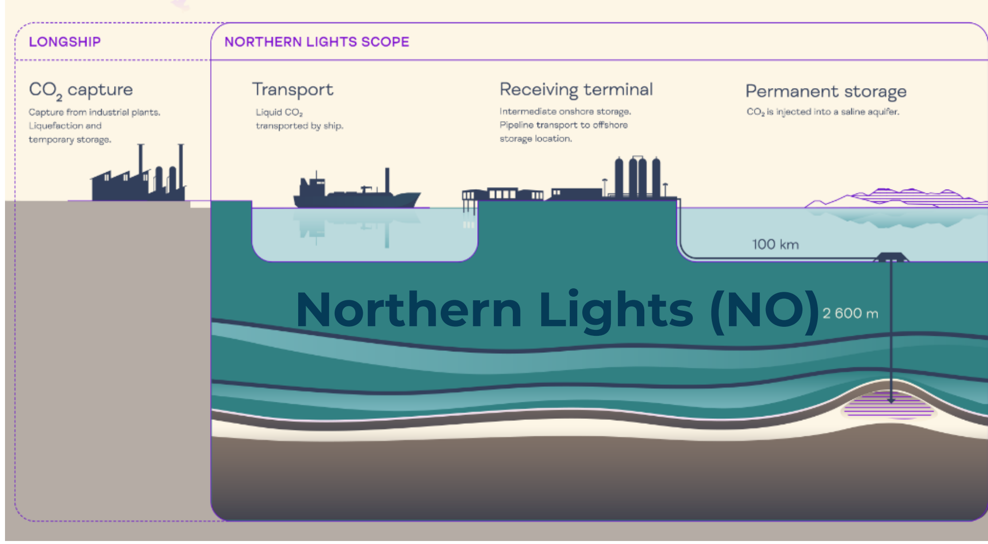


Offshore storage (Example Bifrost) will use depleted offshore oil and gas fields (owned by the Danish Underground Consortium, consisting of TotalEnergies, Noreco and Nordsøfonden) and pipelines connecting to shore (Ørsted).

Maritime Transport
Sailed to an offshore platform and afterwards sent underground via the receiving offshore platform and a dedicated well for the purpose. The CO2 will be permanently stored in a sandstone reservoir 1800 meters below the seabed.



Onshore storage will occur on sites with no previous production (oil and gas). The CO2 will be injected into saline aquifers located subsurface at depths of more than 800m. Multiple storage sites can be connected to the same aquifer, and pressure influence may impact available storage capacity When CO2 is injected, the pressure in the reservoir will increase locally and CO2 will push water away which then will increase the reservoir pressure. Each injection well in the storage sites have an injection rate depending on storage properties.
Capacity is typically between 0.2 and 1.0 MTPA per well



Near-shore storage (Example Northern Lights)
Northern Lights collects the CO2 using newly designed ships, based on standards used for transporting liquified petroleum gas, and takes it to Norway. The CO2 receiving terminal is located in Øygarden on the west coast of Norway. Construction started January 2021. Here there is a temporary buffer storage facility onshore and a 100 km pipeline to the offshore location where the CO2 is injected in to a saline reservoir 2.6 km under the seabed for permanent storage. Rather than using an offshore platform, the injection infrastructure will be installed on the seabed, 300 m below sea level