INNO-CCUS

Direction 2050

Danish CCUS Roadmap 2024

INNO-CCUS
Carbon capture, utilisation, and storage

About this publication:

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Contents

Abbreviations

BECCS
Bioenergy with Carbon Capture and Storage

CCS
Carbon Capture and Storage

CCU
Carbon Capture and Utilization

CCUS
Carbon Capture, Utilization, and Storage

CLC
Chemical Looping Combustion

DAC
Direct Air Capture

DACCS
Direct Air Carbon Capture and Storage

DACCU
Direct Air Carbon Capture and Utilisation

DEA
Danish Energy Agency

EU ETS
European Union Emissions Trading System

EUDP
The Energy Technology Development and Demonstration Programme

FEED
Front End Engineering Design

FID
Final Investment Decision

GEUS
The Geological Survey of Denmark and Greenland

GHG
Greenhouse Gas

IEA
International Energy Agency

IPCC
Intergovernmental Panel on Climate Change

KF24
Danish climate status and outlook 2024

KP22
Danish Climate Programme 2022

LULUCF
Land Use, Land-Use Change, and Forestry

MoU
Memorandum of Understanding

NbSs
Nature-based solutions

OFC
Oxyfuel Combustion

PJ
Petajoule

PRIMES
EU modeling system for evaluating energy policy

SSRL
Storage site readiness level

SSRLE
Societal Readiness Level

TRL
Technology Readiness Level

Danish CCUS Roadmap 2024

Research and innovation for the implementation of CCUS in Denmark

The UN Intergovernmental Panel on Climate Change (IPCC) has repeatedly emphasised necessity of applying carbon capture, utilisation, and storage (CCUS): without it, we simply cannot keep global temperature changes at bay.

CCUS is essential and must play a pivotal role in achieving the goals of a 70% emission reduction by 2030 and net-zero emissions by 2050. The Danish government targets climate neutrality by 2045, which will require even faster emission reductions.
CCUS covers a range of core technologies in the Danish green transition, and Denmark holds extensive expertise across the CCUS technologies and value chain. Denmark has come a long way in a short period of time, and we are well underway with the implementation of crucial technologies, which targeted Danish research has paved the way for.

The Danish CCUS Roadmap 2024 outlines the status of CCUS development in Denmark. From a scientific standpoint, the roadmap provides detailed insight into the development, challenges, and opportunities associated with the key CCUS technologies in Denmark.

Based on that insight, the roadmap offers a perspective on the various paths Denmark can and must take to implement CCUS at the scale required to reach the climate goals. It presents the different strategies ahead and what is necessary for Danish society to make CCUS technologies work together to achieve Denmark's climate targets.

Because there are still obstacles to overcome, room for optimisation, and decisions to be made, to ensure CCUS becomes the decisive player in the green transition, as its potential demonstrates.

With the purpose of strengthening Denmark's position as a frontrunner in the CCUS field, the updated CCUS Roadmap serves as a future national standard for formulating CCUS strategies guiding political ambitions and objectives on reduction quantities and timelines.

To serve this intent, this roadmap consists of four components, which can serve as tools to guide the decision-making for research and innovation within CCUS up to 2030 and 2050.

1. Technology & TRL descriptions:

The roadmap presents a comprehensive list of solutions along the CCS and CCU value chain covering CO_2 capture, nature-based solutions, direct air capture, CO_2 transport, CO_2 storage, CO_2 utilisation and societal coupling. For each solution, the roadmap provides the current TRL, SSRL and SSRLE levels. These levels serve as a framework to assess the maturity of the presented solutions.

→ With this tool it will be possible to track, which solutions are covered by research projects today and where there are solution gaps.

→ The appendix to this roadmap contains a template with a solution tracking list that can be applied to assess which solutions are covered by the projects within a research programme.

2. Innovation demand:

The roadmap identifies innovation and research needs for each presented solution.

→ This tool can be applied to track, if existing projects are addressing the outlined innovation demands and also if new innovation demands are evolving as the roadmap is getting updated.

3. TRL forecast:

The roadmap provides a forecast of time span for the development up to TRL 9 for the identified CCUS solutions along the value chain.

→ With this tool, it can be tracked, if the technologies are developing at the expected pace or if solutions are developing faster or slower than expected. Moreover, it can be assessed, which technologies potentially need enhanced research focus, if they need to be applied within a specific timeframe to reach the climate targets.

4. Technical reduction potentials & 2030/2050 scenarios:

The roadmap compares the DEA 2030 and 2050 scenarios[1] against the technical reduction potentials of CCUS solutions[23] and the Danish climate status & outlook 2024[4]. Moreover, it provides an overview of emission reduction scenarios by the EU[5] and the IEA[6] to put the Danish efforts into an international perspective. By comparing the reduction potentials and scenarios with the current and forecasted TRLs, the roadmap assesses which solutions require an enhanced research focus to reach the climate targets.

→ The update of the DEA scenarios, climate outlook, technical reduction potentials and TRLs in future roadmap updates can be applied to track the development of required mitigation action against the TRL development. This represents a tool to constantly refine and adjust the assessment of research and innovation demands for the presented solutions in this roadmap over time.

The implementation of the CCUS roadmap will be assessed through impact assessment indicators, which will track the development and application of CCUS technologies resulting from Danish research and innovation. These indicators will be published separately from the CCUS roadmap.

Main conclusions

In a 2030 perspective

→ **The analysed DEA scenarios show a strong demand for research into CCUS technologies in a 2030 perspective.**
- In the scenarios, the application of CCS is strongly dependent on the amount of emission reductions from land use and agriculture. The lower the assumed emission reductions from agriculture and land use, the higher the need for negative emissions from CCS solutions

→ **All DEA scenarios apply significant amounts of CO_2 capture from point sources (biogenic & fossil) ranging from ~2-5.5Mtpa in 2030.**
- The technical potential for capture from point sources is estimated to~7-14Mtpa in 2030 (~10.5Mtpa on average) illustrating an even higher emission reduction potential. However, the capture technology has to be mature enough for upscaling in order to deliver sufficient capture volumes.
  - The prevalent capture solutions applied in Danish projects are amine solvents in post-combustion which have a TRL 7-9. However, they are lacking large-scale application in several sectors.
  - Technologies at TRL 9 still need research in supporting technologies around the core technology to ensure an implementation at large scale. This could e.g., be monitoring technologies for CO_2 capture rates and purity.
  - It will need more research into optimisation and scaling of the TRL 7-9 technologies to reach the needed capture volumes for the targeted reductions in 2030.
- The composition of the emitter's flue-/syngas has a high impact on the efficiency of the capture technology. Research should focus the testing of capture technologies on prevalent emitter types in Denmark to identify suitability and higher efficiencies as early as possible in the development process.
  - The prevalent long-term emitters in Denmark are industry production, electricity and district heating production, waste incineration and biogas upgrade.
  - There is a large variety of point source capture solutions with a TRL 6-7, which have potential to be matured to a TRL 9 in a 2030 perspective presuming continuous research efforts.
  - The development of a bigger variety of solutions supports the identification of the most efficient solutions for targeted emitter groups in Denmark.
- Current CO_2 capture solutions for point sources remain to have a high energy penalty which needs to be decreased through enhanced research for realising large-scale application up to 2030.
  - Enhanced application of BECCS will require the availability of sufficient excess renewable energy.
  - At the same time, research should focus on synergy effects and optimal energy system integration with technologies like district heating.

→ **BECCS is assumed to deliver a large share of negative emissions ranging from ~1-3.5Mtpa in 2030 in scenarios with strong CCS focus.**
- The technical potential of point source capture from biogenic sources is estimated to be ~7Mtpa in 2030. This shows that sufficient (and potentially even higher) amounts of biogenic CO_2 from point sources are estimated to be available for capture and storage.
- In the EU scenarios, there are higher capture volumes expected from fossil industry emitters then from biogenic point sources in 2030. However, in a Danish context, industry emissions can also contain biogenic CO_2.

→ **DAC is assumed to deliver ~0.1Mtpa of emission reductions in 2030 in the Bio & CCS scenario. All other scenarios do not consider DAC in this time period. DAC is assumed to have a technical capture potential of 3.5Mt in 2030.**
- The forecasted TRL development shows a TRL 9 maturity of DAC in 2030. If DAC should contribute to reaching the 2030 target with ~0.1Mtpa or up to the assumed technical potential of 3.5Mtpa, stronger research focus into DAC is needed to mature the technology to TRL 9 at a faster pace before 2030.
- None of the 2030 scenarios assume negative emission from DACCS.
- The application of DAC currently has a low cost-efficiency and requires the production of sufficient excess renewable energy for large-scale application.
- Energy intensity, sufficient capture rates and upscaling remain the main challenges for DAC application.

→ **There is a strong focus on reaching negative emissions through pyrolysis (for the production of e.g. biochar) in DEA scenarios building on enhanced application of CCS solutions.**
- Biochar has today a TRL of 6-7 which results in a forecast of reaching TRL 9 in 2030 at a normal technology development rate.
- The scenarios with strong focus on CCS assume negative emissions from pyrolysis of up to ~2.5Mtpa in 2030, which exceeds the assumed technical potential for biochar of 1.7Mtpa. Reaching these volumes requires large scale application already up to 2030 to ensure the delivery of sufficient negative emission in 2030. This requires an enhanced research and innovation focus on biochar to spur a fast TRL development.o The enhanced application of biochar requires the availability of sufficient biomass, which is a scarce resource. It moreover requires sufficient land areal for application and an improved assessment of implementation practices and synergies with the agricultural sector.

→ **There are no assumed emission reductions from CO_2 utilisation in materials and chemicals in 2030.**
- The available storage capacity of at least 14.5Mtpa exceeds the 2.9 Mtpa CO_2 capture covered by the Danish CCS funding schemes and the remaining ~1.5-3.5Mt reduction shortcoming for reaching the 2030 target. This illustrates the demand for import of CO_2 to build a reliable long term business case for storage operators.
- Within storage technology there is need for further site-specific investigations, exploration methods and optimised de-risking workflows.
- There is also a need for more research into the impact of different pressure and temperature levels together with improved exploration methods for the injection and storage of CO_2 in the subsurface.

→ **All presented CO_2 transport solutions (pipeline, shipping, rail, truck) have the potential to reach TRL 9 in 2030 presuming continuous research in all technologies.**
- There is need for proof of large-scale application especially for pipeline and shipping solutions. Large scale application has been proven at a global level, which makes international research cooperation relevant for the development of transport solutions.
- For efficient planning, enhanced research should support development of joint transport infrastructure at regional and national level to enhance synergy effects and ease optimal seizing of infrastructure.
- Important research areas are also the upgrading of harbours for the receival and export of CO_2 and potentials for the retrofitting of existing infrastructure.
- More innovation is also needed in the handling of CO_2 impurities and the monitoring of infrastructure.

→ **The offshore storage projects Greensand and Bifrost and the onshore storage project Stenlille are expected to reach SSRL 9 for large scale CO_2 storage by 2030 with a forecasted storage capacity of at least 14.5Mtpa.**
- The available storage capacity of at least 14.5Mtpa exceeds the 2.9 Mtpa CO_2 capture covered by the Danish CCS funding schemes and the remaining ~1.5-3.5Mt reduction shortcoming for reaching the 2030 target. This illustrates the demand for import of CO_2 to build a reliable long term business case for storage operators.
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→ **The strong focus of the DEA 2030 & 2050 scenarios on negative emissions from biogenic CO_2 requires research into business cases for BECCS and DACCS accompanied by building a robust and reliable voluntary carbon market. There is a need to better understand the development of public acceptance e.g., through surveys to collect useful data on public sentiments regarding perceived risks and attitudes along the value chain, technologies, support mechanisms, distribution of costs and benefits, etc.**

→ **Digital solutions and infrastructure are important to ensure a safe and transparent operation of CCS and CCU value chain.**
- Research and innovation in IoT, cyber-security, digital twins and program verification is necessary.
- Research and innovation in efficient distributed data management, computer vision and machine learning are also required.

→ **The development and implementation of CCUS must take place in accordance with environmental and biodiversity standards.**
- Research on CCUS' impact on environment and biodiversity and results of impact assessments must inform further technology development in the area.

In a 2050 perspective

→ **The analysed scenarios show a strong demand for research into CCUS technologies in a 2050 perspective.**

→ **All DEA 2050 scenarios apply significant amounts of CO_2 capture from point sources (biogenic & fossil) ranging from ~4.5-8Mtpa in 2050.**
- The technical potential for capture from point sources is estimated to ~5-11Mtpa already in 2040 illustrating an even higher emission reduction potential.
- BECCS is assumed to deliver a large share of negative emissions ranging from ~3-6Mtpa in scenarios with strong CCS focus.
  - There is a need for a larger variety and emitter tailored capture solutions to be able to scale capture volumes and profit from efficiency gains for prevalent emitter types.

→ **In 2050, the DEA scenarios are calculating with large amounts of emission reduction from DAC ranging from ~1.5-10Mtpa.**
- In scenarios with high focus on CCS, the volumes of carbon capture from DAC exceed the volumes of capture from point sources by up to 2Mtpa.
- The scenarios have a strong focus on the delivery of negative emissions from DACCS and the utilisation of the CO_2 in DACCU.
  - In scenarios with strong focus on CCS application, DACCS is supposed to deliver ~2.5-5Mtpa negative emissions in 2050.
  - Depending on the scenario, a share of up to ~50% is supposed to be used for DACCU.
    - It has to be considered that DAC and CO_2 utilisation currently are among the CCUS solutions with the highest energy penalty. Applying high volumes of DACCU will require enhanced research into improving energy efficiency for both solutions.
  - The application of DACCS and DACCU require enhanced research in efficient placement of DAC facilities and CO_2 infrastructure planning that incorporates the application of DACCS and DACCU.
- This underlines the general need for more research, faster maturing and faster upscaling of DAC(CS/U) technology to reach the assumed volumes in 2050.
- The EU scenario assumes application of DAC from 2040 building up high capacities of ~180Mt towards 2050.

→ **In 2050, pyrolysis is supposed to deliver ~1.5-2Mtpa which illustrates a continues need for biochar application and the refinement of the technology also beyond 2030.**

→ **Scenarios building less on CO_2 capture from point sources have a stronger focus on NbSs like afforestation.**
- In the 2050 scenarios with higher reductions in agriculture and land use, a bigger amount of afforestation is applied to deliver the remaining negative emissions needed.
- The new marked scenario assumes the biggest share of afforestation with ~3Mtpa, which is a high volume considering that the technical reduction potential from afforestation in 2030 is estimated to 0.5Mt.
- This scenario would therefore require stronger research and implementation efforts into afforestation to reach the assumed capacities in the 2050, considering that forests need time to grow to capture at full capacity.
- This scenario would require utilisation of substantial areas of land, which is in competition with other land use and agricultural activities.

→ **Utilisation of CO_2 in materials and chemicals is currently immature with 50% of the described CO_2 utilisation solutions being below TRL 6.**
- A bigger variety of solutions and better assessment of emission reduction potentials will be needed to ensure the establishment of an atmospheric CO_2 cycle and the phasing out of fossil CO_2 for reaching net zero in 2050.
- EU scenarios assume that emission reductions from CO_2 utilisation in materials and chemicals will only get realised in 2050 with ~50Mtpa CO_2 capture capacity. The scenarios assume the biggest share in reductions from CO_2 utilisation to come from application in green fuels.

→ **In terms of CO_2 storage sites, the overall amount of investigation areas and licenses should be increased to utilise a bigger share of the large storage capacities in the Danish subsurface up to 2050.**

Methodology

The methodology chapter provides an overview of the employed approach for the data collection and analysis of this roadmap.

The data for this roadmap was collected in a fourfold approach:

- → A stakeholder workshop
- → Stakeholder interviews
- → Literature review
- → Ramboll expert consultations

The presented data and conducted analysis in this roadmap are exclusively based on already existing knowledge, publicly available reports and analyses in the field.

For the technology mapping and assessment, scientifically supported technology readiness levels, storage site readiness levels and societal readiness levels were applied to assess the current maturity state of the presented technologies. In order to assess the timeframe in which technologies can reach market maturity at TRL 9, a forecasting methodology was developed based on the input from researchers in the field of CCUS, which will be outlined in the paragraph below.

Technology Readiness Level

Technology Readiness Levels (TRLs) offer a systematic metric measuring the maturity of a particular technology. Initially developed by NASA, TRLs serve as a guideline for technology development from the conceptual stage (TRL 1) to commercial deployment (TRL 9)[1]. The TRL framework assists in consistent communication regarding technology status, supporting decision-making on further development needs, and effectively managing the progression from innovation to market readiness. TRLs are widely utilised to assess the development status of technologies in various industries, ensuring that emerging innovations like CO_2 capture technologies are thoroughly evaluated before they are considered viable for widespread adoption and integration into existing systems. This methodology has become a fundamental tool in managing research and development portfolios, guiding investment decisions, and evaluating the deployment potential and impact of new technological solutions.

Figure 1: TRL definitions by the IEAGHG[2]

Category	Level	Summary
Research	1	Basic principles, observed, initial concept
	2	Formulation of application
	3	Proof-of-concept tests, component level
Development	4	System validation in a laboratory environment
	5	Sub-system validation in a relevant environment
	6	Fully integrated pilot tested in a relevant environment
Demonstration	7	Sub-scale demonstration, fully functional prototype
	8	Commercial demonstration, full scale deployment in final form
	9	Normal commercial service

1 2014-TR4.pdf (ieaghg.org)
2 2014-TR4.pdf (ieaghg.org)

Technology development of TRLs over time

The TRL metric does not indicate timescales of development, because they do not account for the impact of development issues that have to be overcome in the following levels and the time it will take to solve these issues.

The speed of TRL development of a technology is also dependent on several other factors like the amount of available funding, the amount of parallel research projects and the time needed between funding periods to apply for new research projects.

The usual timeframe for TRL development was assessed based on interviews with leading researchers in the field. The estimation of timeframes ranges from minimum one year per TRL from 1-9 to an interval of 3 years per TRL between 1-7 and an interval of about 10 years from 7-9. For the TRL forecast in this roadmap, an average of 2 years per TRL from 1-7 and 3 years per TRL from 7-9 was applied.[3]

The different solutions will be displayed in a comparable table with 5-year steps. Uneven years will be rounded up or down. This means that if it was calculated that the technology should reach a TRL 9 in 2028, it will be categorised in 2030. If it was calculated to reach TRL 9 in 2032, it will be rounded down to 2030. The scheme assumes a similar prioritisation and investment in all presented technologies.

The forecast of TRL development until TRL 9 takes point of departure in known TRLs for the different technologies in 2024. This means that a given TRL from an analysis in 2021 will be assumed to be the same level in 2024. The forecast will be calculated from the assumed level in 2024 and onwards.

Storage site readiness level

Storage site readiness levels (SSRLs) are a new evaluative framework designed to determine the readiness of a CO_2 storage site to become operational. Drawing on expertise from the North Sea's extensive CO_2 storage experience, this system helps outlining the necessary technical evaluation, permitting and planning activities for potential storage sites. Although the methodology was informed by storage portfolios in the UK, Norway and the Netherlands, it is applicable worldwide, including Denmark. Inspired by TRLs used in technological development, SSRLs provide objective measures that align with European legislation's licencing requirements and industry standards, offering a clear path to operational status. This framework can bolster investor and operator confidence by providing estimates of the time and cost required to develop a CO_2 storage site[4].

3 10 Assumptions based on interviews and expert knowledge.
4 Standardised framework provides assessment of carbon dioxide storage site readiness - British Geological Survey (bgs.ac.uk)

Figure 2: SSRL definitions[5]

Level	Summary
1	Basin-wide Screening: Country-wide or basin-scale storage assessment: Identification of a porous rock sealed by a cap rock which lies at a depth greater than 800m. Entire formations may have been identified, although individual sites within these formations may not have been assessed.
2	Storage Atlas ("Play Concept"): Systematic mapping of the potential storage resources of a region. Desktop study that requires sufficient data to enable the first-pass calculation of storage capacity. In some cases, Monte Carlo simulations have been performed and a crude identification of possible geological risks to containment have been undertaken.
3	Screening Study ("Lead evaluation"): Site specific desktop study and initial project concept. All relevant public data is compiled and interpreted. The site will have been considered within the context of a concept for storage or a national portfolio of storage provision. Risks to storage will be identified and data gaps highlighted.
4	Screening Study ("Prospect evaluation"): Validation of desktop studies and revised project concept. This is a detailed assessment and includes various simple geological, geomechanical and simulation models. Once complete, it is possible to proceed to exploration licence application.
5	Exploration Licence & Data Acquisition: Licence has been awarded; the project should be proceeding towards the acquisition of appraisal data. A detailed risk assessment should be in place and the work programme should be looking to reduce risk and uncertainty to an investable level e.g., seismic.
6	Pre-FEED Complete: A comprehensive risk assessment has taken place. Pre-FEED is complete, and the project is ready to proceed to Decision Gate 2 (SELECT to DEFINE). In some cases, the drilling of a well is required to reduce a critical risk.
7	FEED complete. Ready for Storage Licence application: The site has passed all testing in simulated environments and is qualified to store the volumes of CO_2 required by the project. FEED is complete and the project is ready to proceed to Decision Gate 3 (DEFINE to EXECUTE) and take FID.
8	Permitted and Under Construction: Storage licence has been issued and Final FID has been taken. Investment in new infrastructure may occur, subject to permitting e.g., baseline surveys and the construction of injection wells.
9	Operating: Site is operational as a component of an integrated CCS project. A decision to increase the storage capacity of the site would require further characterisation and testing.

Assessment of Societal readiness levels

Societal Readiness Levels (SSRLE), as outlined by the Innovation Fund Denmark, provide a structured framework for evaluating the adaptation of social or technical innovations for integration into society. This system is essential for identifying and executing the steps needed for an innovation to be effectively embedded into community practices, policies, and systems.

5 Standardised framework provides assessment of carbon dioxide storage site readiness - British Geological Survey (bgs.ac.uk)

Figure 3: SSRLE definitions[6]

Level	Summary
1	Identifying problem and identifying societal readiness
2	Formulation of problem, proposed solution(s) and potential impact, expected societal readiness, identifying relevant stakeholders for the project
3	Initial testing of proposed solution(s) together with relevant stakeholders
4	Problem validated through pilot testing in relevant environment to substantiate proposed impact and societal readiness
5	Proposed solution(s) validated, now by relevant stakeholders in the area
6	Solution(s) demonstrated in relevant environment and in co-operation with relevant stakeholders to gain initial feedback on potential impact
7	Refinement of project and/or solution and, if needed, retesting in relevant environment with relevant stakeholders
8	Proposed solution(s) as well as a plan for societal adaptation complete and qualified
9	Actual project solution(s) proven in relevant environment

Figure 4: SSRLE categories[7]

Level	Summary
1-3	Focus on early stages such as problem identification, solution proposals, and initial stakeholder testing. These levels assess societal readiness and engage relevant stakeholders to evaluate potential impacts. This stage is crucial for identifying areas where there might be a lack of acceptance, such as in CO_2 storage projects, where civil society's approval is critical.
4-6	These intermediate stages involve validating the problem and proposed solutions through pilot testing in appropriate environments, emphasizing the testing of the research hypothesis and adaptation of the innovation. During this phase, targeted efforts to increase societal readiness are essential, including engaging municipalities and initiating educational and dialogic interventions.
7-9	The final stages focus on refining, implementing, and disseminating the solution, executing a plan for practical societal readiness to maximize impact and raise awareness. This includes mapping out societal readiness levels and intensifying engagement and information dissemination to overcome any societal resistance.

6 Microsoft Word - Societal readiness levels - SSRL.docx (innovationsfonden.dk)
7 Microsoft Word - Societal readiness levels - SSRL.docx (innovationsfonden.dk)

Applied scenarios for CCUS emission reduction pathways

Danish Energy Agency 2030 & 2050 scenarios (KP22)
The DEA 2030 & 2050 scenarios describe various pathways Denmark might follow to achieve the climate targets set for 2030 and 2050, aligning with the national goal of a 70% reduction in greenhouse gas emissions by 2030 (compared to 1990 levels) and achieving climate neutrality by 2050.

The four scenarios, (1) Bio & CCS (2) Electricity (3) Behaviour (4) New Markets, demonstrate distinct pathways towards achieving the Danish climate goals, each tailored to specific aspects of societal and economic transformation. Central to all scenarios is the commitment to significantly reduce or eliminate unabated fossil fuel use, ramp up renewable energy capacity and achieve net-zero emissions by 2050. As common parameters, the pathways increasing electrification and enhancing energy efficiency as foundational strategies across all pathways.[8]

Figure 5: DEA 2030 & 2050 scenario assumptions

Scenario	Overview	Technologies/ Strategies	2030	2050
Bio & CCS	Relies heavily on bioenergy and CCS technologies.	• BECCS • Afforestation • DACCS • Pyrolysis	Targets moderate reductions by enhancing bioenergy use while beginning to implement CCS technologies: • High reliance on BECCS and afforestation as DACCS and pyrolysis are in early stages	Seeks extensive deployment of negative emission technologies to offset residual emissions, with significant reliance on bioenergy: • 13 million tons CO_2e negative emissions relying on all technologies
Electrification	Prioritises the electrification of various sectors, including transportation, heating and industry.	• Expands renewable energy sources (wind, solar power) • Invests in EV infrastructure and heat pumps	Achieves substantial emissions reductions through the displacement of fossil fuels in electricity generation.	Aims for a fully electrified energy system powered entirely by renewables, significantly reducing dependency on any form of carbon-based fuel.
Behaviour	Assumes significant changes in individual and corporate behavior toward sustainability.	• Energy efficiency • Sustainable building practices • Reduced consumption of high-carbon products (red meat)	Reduces emissions through decreased energy demand and shifts in consumer preferences (e.g., higher uptake of public transport and lower meat consumption).	Continues to build on cultural and behavioral shifts to maintain low energy usage and high sustainability in daily life and business operations.
New markets	Envisions a transformative shift in agriculture from animal-based to plant-based production, alongside growth in green technology sectors.	• Reducing livestock numbers, cutting methane emissions • Expanding markets for plant-based foods and sustainable products	Starts significant reductions in agriculture emissions, initiates change in land use for increased carbon sequestration	Radical restructuring of agriculture coupled with strong growth in new, sustainable market sectors, leads to substantial reductions in greenhouse gases

8 Resultater for KP22-scenarier_clean_23-09-2022_Final_clean (ens.dk)

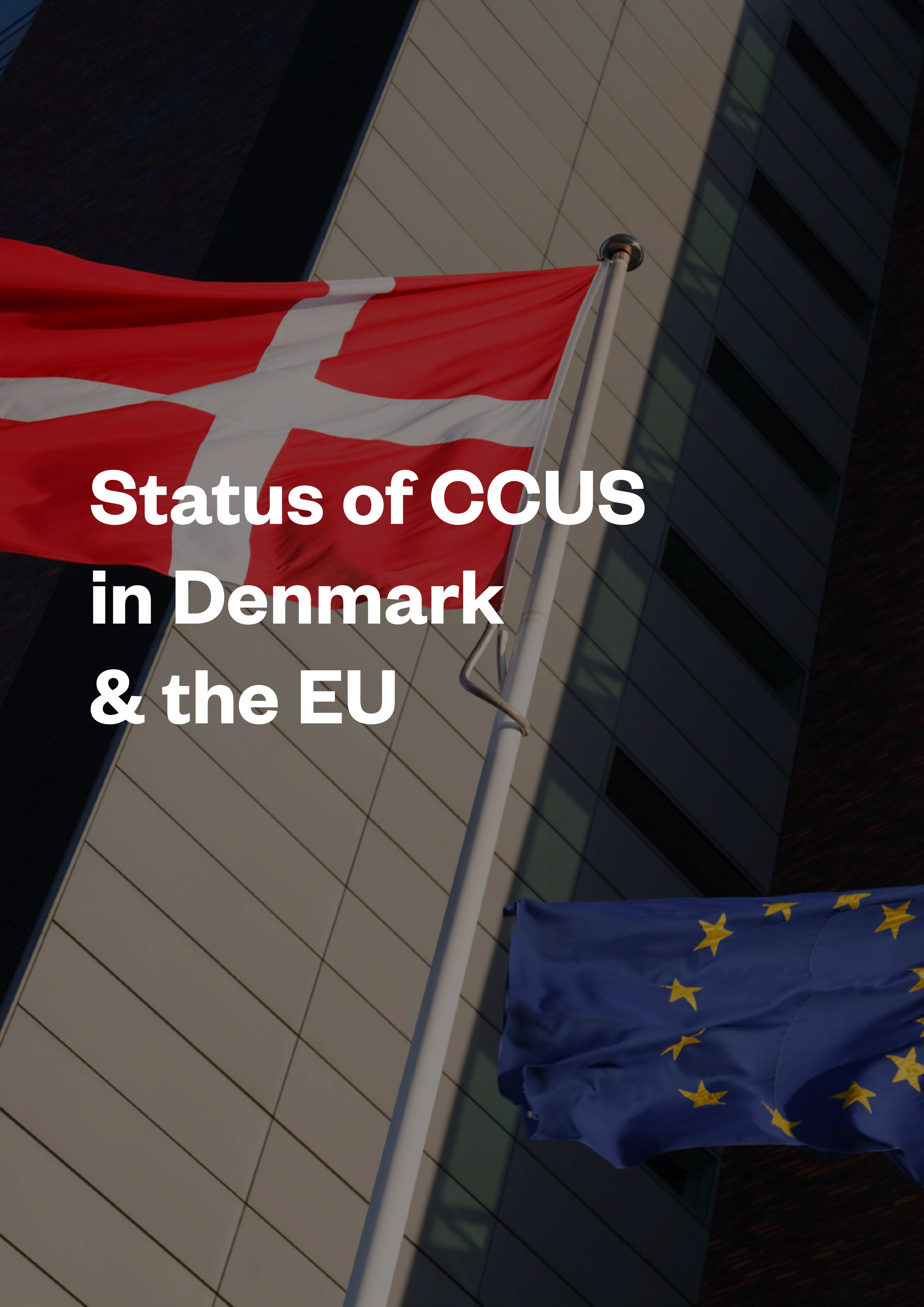
EU scenarios: The EU scenarios apply trajectories as defined by the IPCC and the European Environmental Agency. The EU has developed four GHG emissions pathways (S1, S2, S3 and LIFE) for achieving climate neutrality by 2050, each with their own reduction and contribution of carbon removals. The trajectories are used to assess the potential impacts of different policy measures and evaluate the feasibility of achieving climate targets under different scenarios.[9]

- → The S1 scenario is the most conservative EU scenario towards net zero in 2050. S1 aims for total net GHG emissions of around 1050 $MtCO_2$-eq by 2030, potentially ranging down to 890 $MtCO_2$-eq depending on LULUCF net removals behavior. This represents a reduction of 78% compared to 1990 levels. The scenario prioritises strengthening existing trends with limited integration of advanced mitigation options and novel technologies by 2040. It follows a linear trajectory of net GHG emissions reduction from 2030 to achieve climate neutrality by 2050. This scenario sets a remaining GHG budget of 21 $GtCO_2$-eq for the period 2030-2050. Significant additional reductions are expected in power and heat, industry and agriculture compared to other scenarios.
- → In S2, existing decarbonisation methods like electrification and renewables are maximised. Additionally, it integrates CCU technologies and increases the adoption of e-fuels derived from fossil-free carbon sources. By 2040, S2 aims to achieve an 88% reduction in emissions compared to 1990 levels, reaching about 580 $MtCO_2$-eq. The scenario sets a remaining GHG budget of 18 $GtCO_2$-eq for the period 2030-2050, targeting emissions reductions of at least 85% up to 90%. By 2040, S2 anticipates further reductions, reaching around 940 $MtCO_2$-eq or an 80% reduction compared to 1990.
- → The S3 scenario pursues early deployment of novel technologies to achieve profound reductions in greenhouse gas (GHG) emissions. By 2040, this scenario targets net GHG emissions at approximately 356 million tons of CO_2-equivalent ($MtCO_2$-eq), representing a reduction of 92% compared to 1990 levels. The reductions could range between 90% to 94%, highlighting a strong emphasis on surpassing conventional decarbonisation methods. This scenario leans heavily on rapid technological advancement and early adoption, setting ambitious goals to substantially lower emissions ahead of the curve.
- → The LIFE scenario integrates additional circular economy actions and emphasises sufficiency in industrial processes, transport and agriculture to achieve its climate targets. This approach results in net GHG emissions similar to those of the S3 scenario by 2040, at approximately 353 $MtCO_2$-eq, with a reduction range also from 90% to 94%. By 2050, the LIFE scenario projects a net GHG emission of about -70 $MtCO_2$-eq, suggesting that it not only reaches net-zero emissions but achieves net-negative emissions, indicating the removal of more GHGs from the atmosphere than it emits. This scenario uniquely combines aggressive emissions reductions with enhancements in environmental performance by reducing the consumption of natural resources.[10]

Global IEA scenarios: The Global IEA scenario is based on the 2023 Net Zero Emissions (NZE) trajectory for the global energy sector to attain net-zero CO_2 emissions by 2050, in line with the Paris Agreement. Advanced economies lead by achieving net-zero emissions earlier, with emerging market and developing economies following suit. By 2030, global access to electricity and clean cooking is targeted, with major reductions in methane emissions from the oil, gas and coal sectors. This paves the way for less abrupt CO_2 reductions in emerging markets and developing economies, aiming for an 88% reduction compared to 1990 levels by 2040. Global collaboration is essential, driving down technology costs and scaling up resilient supply chains for critical minerals and clean energy technologies. Financial support to emerging market and developing economies is crucial for equitable pathways to net-zero emissions.[11]

9 pdf (europa.eu)
10 pdf (europa.eu)
11 Net Zero Roadmap, A Global Pathway to Keep the 1.5C Goal in Reach, IEA

Status of CCUS in Denmark & the EU



Status of CCUS in Denmark & the EU

Denmark has since 2020 built a comprehensive regulatory framework for CCUS. This chapter provides an overview of the established legislation and market incentives that Denmark has implemented over the last four years. The chapter also provides an overview of targets in the EU Carbon Management strategy to put the Danish potentials and actions into an international perspective.

Political agreements

→ Agreement to legalise CCS and allocate DKK 16.6 billion (EUR 2.2 billion) under the Danish climate agreement in June 2020.
→ Agreement to legalise import/export of CO_2, to make DK a European hub for CCS, and to roll out CCS on market terms in the long run in the CCS strategy from 30 June 2021 and 14 Dec. 2021.
→ Agreement in the Danish Financial Act from 2022 to allocate DKK 2.6 billion (EUR 0.4 billion) to achieve negative emissions.
→ Agreement on state co-ownership of storage permits + pilot project in Stenlille 21 June 2022.
→ Agreement on the Green Taxation Reform for industry of 24 June 2022 with DKK 19.5 billion (2.6 billion EUR) dedicated to CCS.
→ Agreement on strengthened framework conditions for CCS in Denmark on 20 September 2023.
  - Merging of the CCUS and the Green Taxation Reform funding scheme to a joint scheme over DKK ~27billion to deliver 2.3 million tons per year from 2029.
  - The agreement creates greater security for full capture and storage of CO_2 as early as 2029 – and at the same time removes obstacles and creates clarity regarding the establishment of both pipes and the transport of CO_2 and the development of CO_2 storages.[12]

Legislation

→ Faster and less extensive approval process for storage pilot projects in the North Sea entered into force on 1 July 2022.
→ Exempting storage and transport of CO_2 from the prohibitions against dumping in the Marine Environment Act entered into force 1 August 2022.
→ Upcoming framework conditions for pipeline-based CO_2 transport (summer 2024).

Implementation

→ Awarding of offshore exploration licenses to INEOS Energy and Total Energies.
→ Awarding of the first round of the CCUS funding scheme to Ørsted in 2023.
→ GEUS finished seismic preliminary studies of possible storage structures on land and near the coast. Start of Environmental Impact assessments.
→ MoU on CCUS with the Netherlands + Belgium, Norway, Sweden and France with the aim of promoting CCUS.
→ Awarding of the first round of the NECCS funding scheme in April 2024.
→ Tendering of onshore and nearshore storage licences with awarding expected in 2024.[13]

National funding schemes

The Danish government has introduced three funding schemes for CCUS:

12 Cover (ens.dk)
13 Slides ccus forum (kefm.dk)

Figure 6: Overview of Danish funding schemes

	Category	Political agreement	Capture volume	Funding volume	Awarding	First year of reduction
1. Funding scheme	CCUS	Danish climate agreement	0.43 million tons CO_2	DKK 8 billion	2023 to Ørsted	2026
2. Funding scheme	NECCS	Danish Finance Act	160,350 tons CO_2	DKK 2.5 billion	April 2024 to BioCirc CO_2 ApS, Bioman ApS, Carbon Capture Scotland Limited	2026
3. Funding scheme (merged)	CCS	Danish climate agreement & Danish Green Tax Reform	2.3 million tons CO_2	DKK ~27 billion	Two tender rounds in: 2024 (10.5 billion DKK / 1.4 million tons) and 2025 (1.4 million tons / 16.3 billion DKK)	2029

Incentives for CCUS in DK

The primary drivers behind the advancement of CCUS encompass a combination of factors, namely 1) national funding initiatives, 2) participation in the EU ETS and 3) the implementation of a domestic carbon pricing mechanism.

In Denmark, the EU ETS encompasses various sectors, including waste incineration and major industrial processes like cement production, which significantly contribute to the country's industrial emissions. While the ETS prices provide some impetus for emission reductions, they may not be adequate to drive the necessary cuts across all sectors to meet Denmark's climate target by 2030.

In 2022, a majority of the Danish parliament reached consensus on implementing a carbon tax across most sectors, excluding road transportation, agriculture and land-use. The tax rates vary by sector and industry, with gradual implementation scheduled from 2025 to 2030. For non-ETS industries, the tax floor is set at 100 EUR/ton, while for ETS industries, it stands at~50 EUR/ton, in addition to the EU ETS price. Mineralogical processes face an additional tax on top of the EUR 100 price floor of ~15 EUR/ton.

The EU Carbon Management Strategy in a Danish context

The EU Industrial Carbon Management Strategy was passed on 6th February 2024 and provides a comprehensive framework to achieve carbon neutrality in the industrial sectors as outlined in the Net Zero Industry Act. The strategy sets ambitious targets for CCS, promoting investments in low-carbon technologies, and encouraging the adoption of carbon removal and utilisation methods.
It is directed to inform and guide legislation and implementation at the national level. Denmark, along with other EU member states, will need to collaborate to identify suitable CO_2 storage locations, develop infrastructure and establish common regulatory frameworks. The deployment of CO_2 transport networks, especially in southern and eastern Europe, will be crucial for the efficient transportation of captured CO_2 over long distances. Additionally, early adoption of CO_2 transport infrastructure will have a significant impact on shaping the evolution of the network.

From a fossil to an atmospheric CO_2 cycle

From a fossil to an atmospheric CO_2 cycle

Targets:

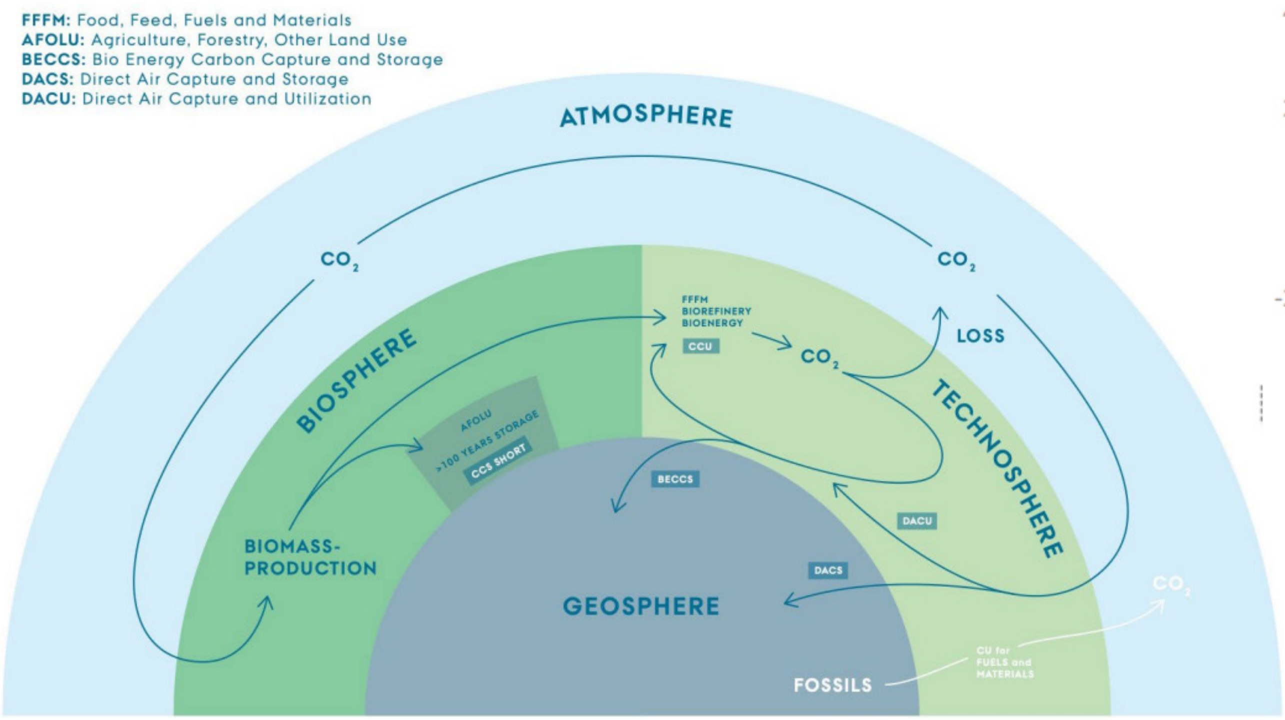
→ 50 million tons of CO_2 per year captured in the EU by 2030.
→ Approximately 280 million tons of CO_2 per year would need to be captured in the EU by 2040.
→ Up to 450 million tons of CO_2 per year captured in the EU by 2050.
→ By 2040, about half of the captured CO_2 would have to come from biogenic sources or directly from the atmosphere.
→ At least 250 million tons of CO_2 per year stored geologically in the European Economic Area in 2040.

Projections:

→ Projections suggest that the CO_2 transport infrastructure might extend over a distance of up to 7300 km by 2030, with an associated deployment expense of up to EUR 12.2 billion, projected to increase to approximately 19,000 km and EUR 16 billion by 2040.
→ Theoretical EU market potential of 360 to 790 million tons of captured CO_2 could lead to a total economic value between EUR 45 billion and EUR 100 billion, contributing to the creation of up to 170,000 net-zero jobs.

The current society and industry rely heavily on fossil hydrocarbons for energy and chemicals, leading to a linear flow of extraction of carbon to CO_2 emissions into the atmosphere. A sustainable future requires shifting away from this linear model, viewing CO_2 as a valuable resource in a circular carbon economy. Simply relying on CCUS is not enough to stabilise atmospheric CO_2 levels. Therefore, by 2030, we must minimise fossil carbon sources, phase out their use in energy, and plan for long-term carbon storage to compensate. By 2050, society needs to transition using atmospheric CO_2 for chemicals, materials and some fuels. Phasing out fossil carbon extraction will reduce emissions and incentivise capturing atmospheric CO_2. In the short term, this transition is crucial to move towards a CO_2-neutral future. Ultimately, it will lead to a net-negative state, where atmospheric CO_2 is utilised and stored, creating a circular system that continuously captures more carbon than it emits.

Figure 7: Overview of CO_2 cycles

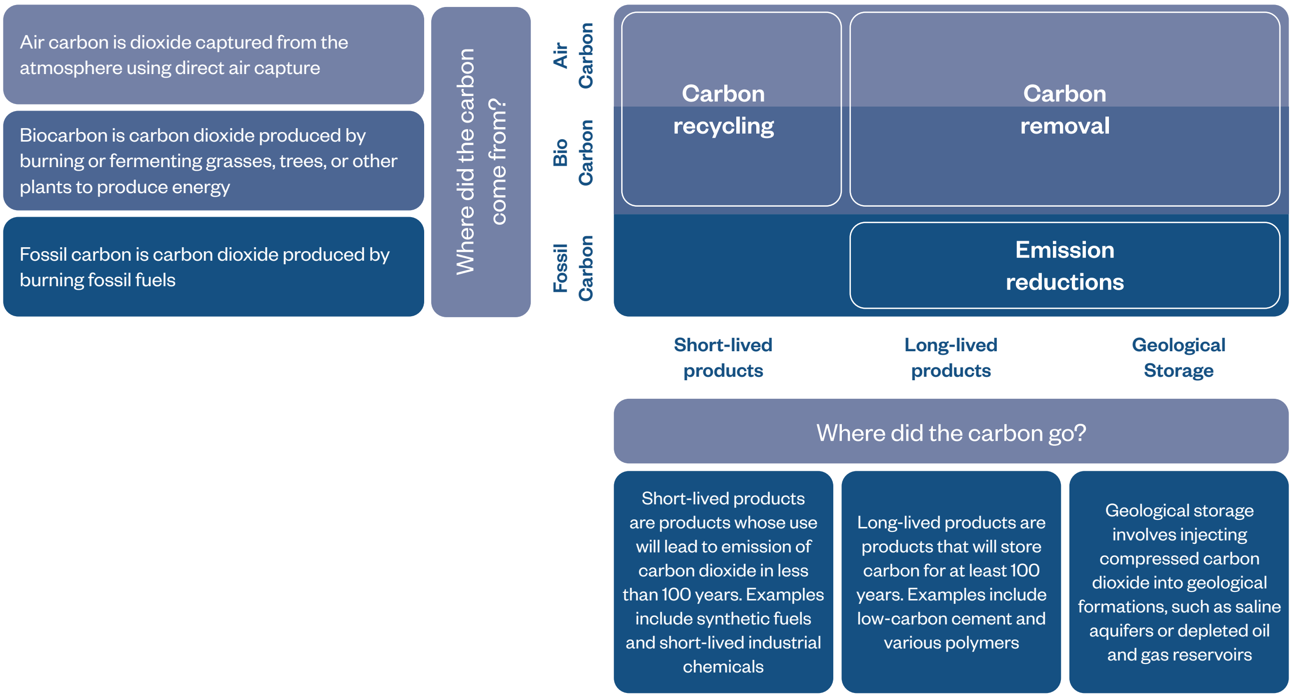


CO_2 sources

The source of CO_2 and the subsequent use has a large impact on the resulting net emissions. For an atmospheric carbon source (non-fossil) such as biomass, the collected CO_2 has just recently been removed from the atmosphere. The storing of the collected CO_2 will result in a net removal of CO_2 from the atmosphere. Accordingly, sequestration of fossil CO_2 can facilitate carbon emission reductions, but to remove CO_2 from the atmosphere, the CO_2 must originate from a source that absorbed the CO_2 from the atmosphere. Long-term storage can also include storage in ecosystems and sediments or uptake in concrete. The impact of the source and use of the CO_2 is shown in figures 7 and 8.

The CO_2 source must be verifiably sustainable. This means, for instance, that biomass must be harvested sustainably, which ensures that a similar amount of biomass is being regrown. This must furthermore be verifiable through regulation structures and certificates.

Figure 8: Reduce, Remove, Recycle: Clarifying the Overlap between Carbon Removal and CCUS, American University, 2020



CCUS solution mapping

CCUS Solution mapping

CCUS solution mapping

The following chapter contains a comprehensive CCUS solution mapping along the entire value chain. The mapping covers CO_2 capture from point sources, nature-based CO_2 capture, CO_2 transport, geological CO_2 storage and CO_2 utilisation (excluding green fuels). Each solution chapter consists of the following sections:

- → A short solution description
- → An overview of innovation and R&D demands
- → An assessment of the current TRL/SSRL of the solution
- → A forecast of the technology development to TRL 9
- → A conclusion section

The identified innovation and R&D demands are non-exhaustive and supposed to illustrate an overarching picture of areas which future research and innovation can be oriented towards.

CO_2 capture from point sources

CO_2 capture from point sources

CO_2 capture from point sources describes the process in which CO_2 is captured directly from flue gas or syngas at the emitter facility instead of releasing the CO_2 into the atmosphere. The Danish Energy Agency (DEA) categorises four main groups of CO_2 point sources in Denmark: Waste incineration, electricity and district heating production, industry and biogas upgrade.

The gas compositions and CO_2 concentrations differ among the emitters, which has an influence on the applied capture technology and efficiency.

Innovation and R&D

CO_2 capture technologies can be categorised in four basic types:

Pre-combustion: The raw fuel undergoes pre-treatment, converting it into a mixture of CO_2 and clean fuel/syngas. The CO_2 is then separated and the clean fuel/syngas can be used for other typically combustion based applications such as power generation or heat production. Typical for pre-combustion applications are often high CO_2 concentrations in an atmosphere with no (or very little oxygen). The gas to be treated may also be at elevated pressures. There is an overlap between pre- and post-combustion technologies, although suitability and challenges for the technologies will vary.

Gasification: Gasification is a technology especially relevant for converting solid feedstocks like coal, biomass or waste materials into syngas (a mixture of hydrogen and carbon monoxide that later converts to CO_2). This process produces clean hydrogen and integrates CO_2 capture as a parallel benefit. The development and commercialisation of gasification technology is essential for enabling effective pre-combustion capture, with ongoing advancements aimed at improving efficiency and reducing the costs associated with syngas cleaning and CO_2 separation.

Natural gas for blue hydrogen: An emerging avenue within pre-combustion technology is the production of blue hydrogen, where natural gas is processed through steam methane reforming to separate hydrogen and CO_2. The hydrogen produced is relatively low in carbon footprint, provided the CO_2 byproduct is captured and stored or utilised effectively. The technology provides a transitional solution towards more sustainable energy systems while green hydrogen technologies are being developed and scaled.

Integration with renewable energy and sector coupling: Pre-combustion carbon capture technologies offer opportunities for integration with renewable energy sources. For instance, excess heat from hydrogen production processes can be utilised in district heating or other industrial processes, enhancing overall system effectiveness and enabling sector coupling. This integration helps in optimising energy use and reducing waste, contributing to more sustainable and resilient energy systems.

Biogas upgrade: Upgrading biogas to enhance its calorific value involves separating CO_2 from methane, traditionally through energy-intensive methods and environmental impact. Recent innovations focus on sustainable alternatives like ionic liquids, deep eutectic solvents, and clathrate hydrates, known for their low environmental impact and high CO_2 /CH4 selectivity, which minimises methane loss. These emerging technologies promise more efficient and eco-friendly biogas upgrading, essential for integrating into pre-combustion carbon capture systems. Challenges in scalability and optimisation remain. Moreover, biogas upgrade usually covers small point source emitters, which can pose challenges in reaching commercial volumes and logistical challenges for transport and storage/utilisation.

Challenges and outlook: Despite the opportunities, pre-combustion capture faces challenges including high capital costs, technological complexity and requires significant energy inputs for gas process and CO_2 compression. Future research and development are focused on enhancing process efficiencies, reducing costs and integrating advanced materials and technologies such as novel solvents, sorbents and membrane technologies to improve the performance and economic viability of pre-combustion carbon capture.

Oxyfuel combustion: Oxyfuel combustion leverages pure oxygen for the combustion of fuels instead of air. This approach significantly alters the composition of exhaust gases, predominantly producing water vapor and CO_2. This results in a high-purity CO_2 stream post-combustion, facilitating easier and more efficient carbon capture.

Waste oxygen utilisation: In energy systems integrating power-to-x technologies, oxyfuel combustion can effectively utilise waste oxygen generated by electrolysers. This synergy could further enhance the sustainability of such systems by enabling the captured CO_2 to be used in the production of green fuels, supporting the establishment of a circular carbon economy.

Retrofit challenges and economic considerations: Retrofitting existing boilers to accommodate oxy- circulating fluidized bed facilities by increasing oxygen levels to 50-80% presents significant challenges due to the constraints of existing furnace dimensions and infrastructure. The cost implications and technical modifications required, including the addition of air separation units and carbon capture units, make retrofitting complex and costly. The likelihood of developing a feasible retrofit solution within the operational lifespan of current boilers remains low.

Outlook: Oxyfuel combustion holds promise for reducing carbon emissions in the cement industry by producing a concentrated CO_2 stream that simplifies capture processes. Ongoing research is essential to overcome the technical and economic challenges of this technology. Developing adaptable solutions that integrate seamlessly with both existing and new industrial frameworks, optimising energy consumption, and minimising environmental impacts are critical. Collaborative efforts across industry and academia are vital to harness the full potential of oxyfuel combustion for large-scale carbon capture and decarbonisation.

Chemical looping combustion: Chemical looping combustion (CLC) is a capture technology that integrates CO_2 capture directly with the combustion of hydrocarbon fuels using a dual-reactor system. This system comprises a fuel reactor where combustion occurs with oxygen delivered by metal oxides and an air reactor where these oxides are regenerated. Oxygen carriers such as iron, manganese, copper, nickel, and cobalt transfer oxygen from the air to the fuel, allowing for direct capture of CO_2 from the exhaust without the need for additional gas separation processes. This setup not only simplifies the overall process but also reduces the energy penalty typically associated with CO_2 capture, enhancing both efficiency and cost-effectiveness.

Operational Challenges and Solutions: Challenges for the technology include the mechanical and chemical stability of oxygen carriers, the design and operation of fluidised bed reactors that can handle the dual-task of effective gas-solid contact and solid circulation without leading to attrition or agglomeration of the carriers. Overcoming these challenges is crucial for the successful scale-up and commercial deployment of CLC systems.

Current Research and outlook: Recent advancements in CLC research focus on improving the energy efficiency and durability of the oxygen carriers, developing more robust reactor designs, and integrating CLC systems with existing power generation infrastructures. Some studies also explore the potential of using biomass and integrating waste heat utilisation systems to further enhance the sustainability and efficiency of CLC processes. The integration of CLC with renewable energy sources and its potential to adapt to fluctuating energy demands make it a compelling option for future power systems that aim for high operational flexibility and minimal environmental impact.

Post-combustion: In this process, the CO_2 is captured from exhaust gases of combusted fuels. For post-combustion applications, several technologies are available, the most used one being liquid solvents like amine, which currently are the prevalent solution applied in CCUS projects under implementation in Denmark. Amine-based solvents are fast at absorbing CO_2 in the scrubber unit but the subsequent release in the stripper requires temperatures around 120°C. In an absorption-based approach, the solvent absorbs the CO_2, which is then released by heating. This is a known technology that is applied e.g., in the food and beverage industry. The technology is however lacking implementation in large scale projects. Post-combustion technologies are currently easier to retrofit to existing emitters and interfere less with the existing production process than most pre-, oxyfuel and chemical looping combustion technologies. However, due to the late integration of the CO_2 capture in the production process, the CO_2 concentration is lower than in earlier production stages which in many cases causes higher energy penalties to separate the CO_2 from the gas.

Energy use & efficiency: In recent decades, research has focused on improving amine solvents through lower energy usage, increased cyclic capacity, improved resistance to degradation and better environmental properties. Although advancements have reduced energy and chemical consumption in current amine processes, it remains considerable. Efforts to develop heat-resistant amine processes that yield CO_2 at higher pressure, reducing costly compression, are underway. While further improvements in amine solvents are possible, they may not drastically reduce energy consumption. Research into alternative solvents, such as non-aqueous or engineered compounds, holds promise but is uncertain. Research into alternatives to amine-based solvents, such as non-aqueous solvents, enzyme promoted solvents, Benfield process type solvents, phase changing solvents, solid sorbents and other engineering compounds holds promise, but are not yet proven in scale for post-combustion applications. Advanced process flowsheets with enhanced heat integration are also being explored to lower energy requirements. Some suppliers are implementing these solutions. Another research area to enhance synergy effects is sector coupling through utilisation of excess heat from CO_2 capture in district heating systems. Ongoing research focuses on integrating carbon capture with energy plants, with heat pump technology showing potential to improve overall energy efficiency. Equipment suppliers are developing optimised solutions for carbon capture, which could significantly reduce capital expenditure in the mid- to long-term, pending widespread adoption in the large-scale carbon capture market.

Corrosivity & toxic degradation: Amine-based solvents are corrosive and release toxic degradation products. Further developments within new less tested solvents systems containing biocatalysts are needed as these offer a possibility to improve the cost and environmental impact of carbon capture processes.

Energy system: CO_2 capture technologies today run on dedicated energy supply systems. Other technologies producing excess heat like hydrogen production could be coupled to CO_2 capture facilities allowing for capture technologies driven by low-cost waste heat from a variety of sources. A transition phase for the capture technology could include application of large heat pumps where CO_2 capture will be able to use or supply excess heat to other processes and district heating allowing for optimal sector coupling. In the future, there will likely be periods with scarcity of electricity due to the pure nature of green resources, which are not always available in time. The CO_2 capture technology must be able to operate in a flexible manner allowing for a part load and a full load 100 % capture strategy.

The first full value chain CCS project with post-combustion application in Denmark is the Ørsted Kalundborg CO_2 Hub with the goal of capturing 430,000 tons of CO_2 annually and a planned capture start in 2026. The project will capture CO_2 from the woodchip-fired Asnæs Power Station in Kalundborg and the straw-fired unit at Avedøre Power Station in Greater Copenhagen. The captured CO_2 will be biogenic and is thereby generating negative emissions.
The project applies advanced amine-based carbon capture technology.

Technology optimisation demands:

Impurities: Impurities in the CO_2 stream can vary in composition and impact the efficiency and durability of capture technologies. Examples are sulphur compounds which corrode equipment leading to reduced CO_2 capture efficiencies, NOx emissions interfere with solvent performance and PM fouls adsorbents reduce surface area and overall system performance. There is need for advanced filtration and purification processes to address this issue.

Material selection and optimisation: The materials used within capture technologies must resist the harsh conditions they are exposed to, such as corrosiveness and abrasiveness of gas streams.

Materials for capture facilities: Currently applied are various forms of stainless steels, fibre reinforced plastics (FRP), FRP lined concrete/brick absorbers and various forms of packing material. The choice of material is usually a trade-off between corrosion resistance, strength and cost.

Material durability and corrosion resistance in the capture process: Materials like metal–organic frameworks (MOFs) and zeolites have shown promise in CO_2 capture due to their high surface area and selectivity. However, their stability in the presence of moisture and acidic gases needs enhancement to prevent degradation.

Abrasion tolerance & structural integrity: Solid sorbents, often functionalised with amines, must maintain their physical structure under the mechanical stress caused by gas flow. Research is directed towards improving the binding of amines to the sorbent's surface to prevent their wear down.

Chemical stability: Ionic liquids have a low vapor pressure and can capture CO_2 effectively. The challenge lies in ensuring that their chemical structure remains intact over repeated absorption-desorption cycles.

Long term and robust operation: The aspect of long-term operation and robustness of CO_2 capture systems is crucial for their sustainable integration into industrial processes. Ensuring these systems maintain efficiency over prolonged periods, during variable operational conditions, is a goal that demands continual innovation.

Implementation of AI in new technology development: The implementation of artificial intelligence in the development of new technologies offers a transformative potential for CO_2 capture. AI can optimise the capture process, forecast maintenance needs, and heighten overall system efficiency. The intersection of AI and industrial process optimisation is an emerging focus area in academic and industry research, with abundant untapped potential for innovation.

Solvent degradation, reclaiming and emission control: Issues of solvent degradation and the potential for reclaiming used solvents are further challenges. Over time, the solvents integral to capturing CO_2 can lose their efficiency, necessitating research into enhancing solvent stability and regeneration techniques. The chemical industry is actively exploring this, searching for ways to extend the lifecycle of solvents and uncovering new methods of solvent reclamation[47]. Another important factor is improvement of monitoring techniques for emission control.

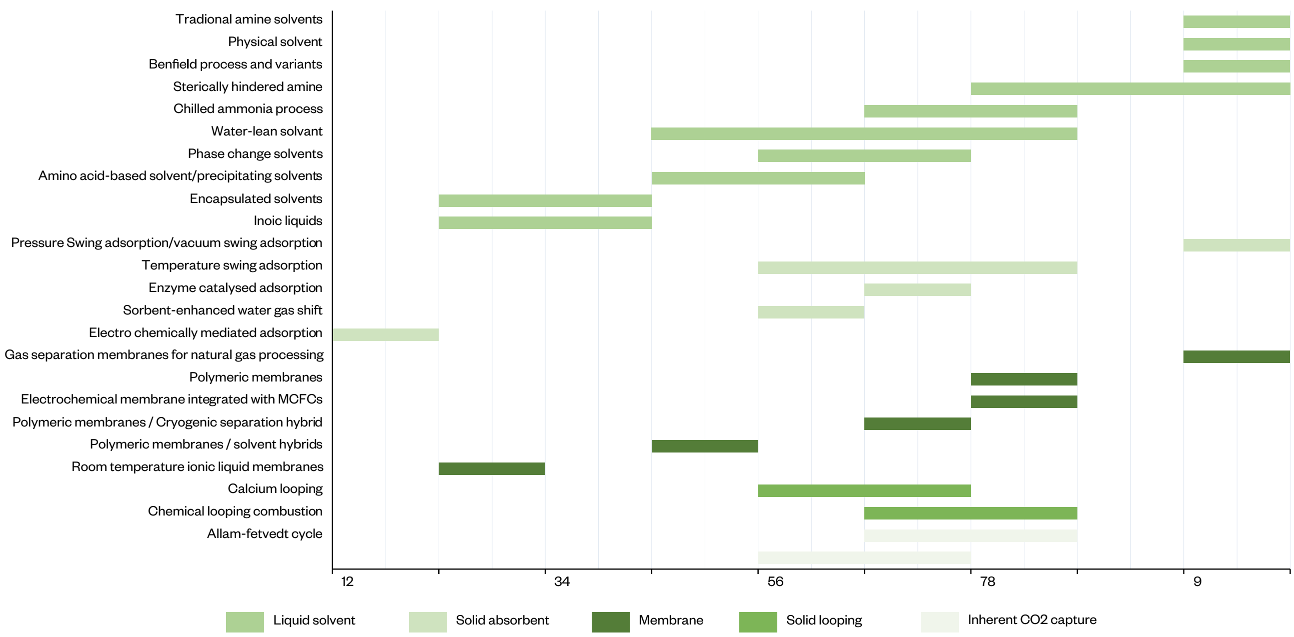
Upscaling feasibility: A joint challenge for the presented solutions is to proof upscaling feasibility to reach commercialisation. In case of CO_2 capture technologies this does not only apply to proofing upscaling capacity at a number of emitters, but also the type of emitters. As outline earlier, the capture efficiency is highly dependent on the gas composition of different emitter types. It is therefore important to assess, if a capture technology can be upscaled for several emitter types or if it is particularly efficient for specific emitter types like for instance oxyfuel combustion for cement.

Simpler and online analysis of gases, solvents, devices etc.: There is need for simpler and more immediate analysis of gases, solvents, and devices to reach real-time monitoring and control in industrial processes. The goal is to develop methodologies that allow for the immediate analysis and adjustments, ensuring capture systems operate at peak performance. Advancements in analytical chemistry can lead the way toward smarter, faster process monitoring tools.

Current TRL for CO_2 point sources capture solutions

Figure 9 provides an overview of TRLs for CO_2 capture solutions for point sources divided by the medium that is used to separate the CO_2 from a gas stream. The TRLs were assessed by the Global CCS Institute.

Figure 9: TRLs for CO_2 point source capture solutions



TRL forecast for CO_2 point source capture solutions

Figure 10 provides a forecast on the estimated time period that it would take the presented CO_2 capture solutions to reach TRL 9 assuming a regular TRL development with continuous research efforts for each technology.

Figure 10: TRL forecast for CO_2 point source capture solutions

Technology	Status 2024	2030	2035	2040	2045	2050
Liquid solvent						
Traditional amine solvents	7-9*	9				
Physical solvent	7-9*	9				
Benfield process and variants	7-9*	9				
Sterically hindered amine	6-9	9				
Chilled ammonia process	6-7	9				
Technology	**Status 2024**	**2030**	**2035**	**2040**	**2045**	**2050**
Water-lean solvent	4-7		9			
Phase change solvents	5-6		9			
Amino acid-based solvent/precipitating solvents	4-5		9			
Encapsulated solvents	2-3			9		
Ionic liquids	2-3			9		
Solid absorbent	**Status 2024**	**2030**	**2035**	**2040**	**2045**	**2050**
Pressure Swing adsorption/vacuum swing adsorption	9					
Temperature swing adsorption	5-7		9			
Enzyme catalysed adsorption	6	9				
Sorbent-enhanced water gas shift	5		9			
Electro chemically mediated adsorption	1					
Membrane	**Status 2024**	**2030**	**2035**	**2040**	**2045**	**2050**
Gas separation membranes for natural gas processing	9					
Polymeric membranes	7	9				
Electrochemical membrane integrated with MCFCs	7	9				
Polymeric membranes/Cryogenic separation hybrid	6	9				
Polymeric membranes/solvent hybrids	4		9			
Room temperature ionic liquid membranes	2			9		
Solid looping	**Status 2024**	**2030**	**2035**	**2040**	**2045**	**2050**
Chemical Looping	6-7	9				

Calcium looping combustion	5-6		9			
Inherent CO_2 capture	**Status 2024**	**2030**	**2035**	**2040**	**2045**	**2050**
Calix Advanced Cycle			9			
Allam-fetvedt cycle		9				

**In a Danish context, the first three capture solutions are assumed to have a TRL 7-9 instead of the presented TRL 9 by the Global CCS Institute. The technologies may be TRL 9 in some applications (like gas sweetening or other pre-combustion areas), but for the post-combustion applications we expect to introduce carbon capture at scale up to 2030. There are none to only few operating plants worldwide.*

Conclusions

- The application of CO_2 capture for point sources has a strong focus on capturing CO_2 emissions from already existing plants. The ability of capture solutions to be integrated in existing facilities via retrofitting is an important factor for the implementation of these solutions.
- Post-combustion solutions are currently the most applied CO_2 capture solutions in a Danish context. They are well-suited for retrofitting of existing emitters.
- Post-combustion applications remain to have a high energy penalty. More research into energy efficiency and upscaling possibilities is required.
- Pre-combustion, oxyfuel combustion and chemical looping combustion are more difficult to retrofit but have potentials for higher energy savings e.g. because of the comparably high CO_2 concentration of the gas stream in earlier stages of production compared to post-combustion.
- Pre-combustion, oxyfuel combustion and chemical looping remain to be rather immature technologies. Their large-scale implementation should be considered in a post 2030 perspective presuming continuous research in these solutions.
- Some solutions show special suitability for specific emitter types (e.g. oxyfuel combustion in the cement industry). This suggests that testing of point source capture technologies should address targeted emitter types in Denmark to identify suitability and efficiency for specific emitter types as early as possible in the development process.
- Continuous refining and optimisation of the core capture solutions and supporting technologies is needed, even if a solution has reached TRL 9. This demonstrates the need for continues collaboration between universities and the industry also after implementation of the solutions to ensure effective long-term operation. This applies to technologies along the entire CCS and CCU value chain.

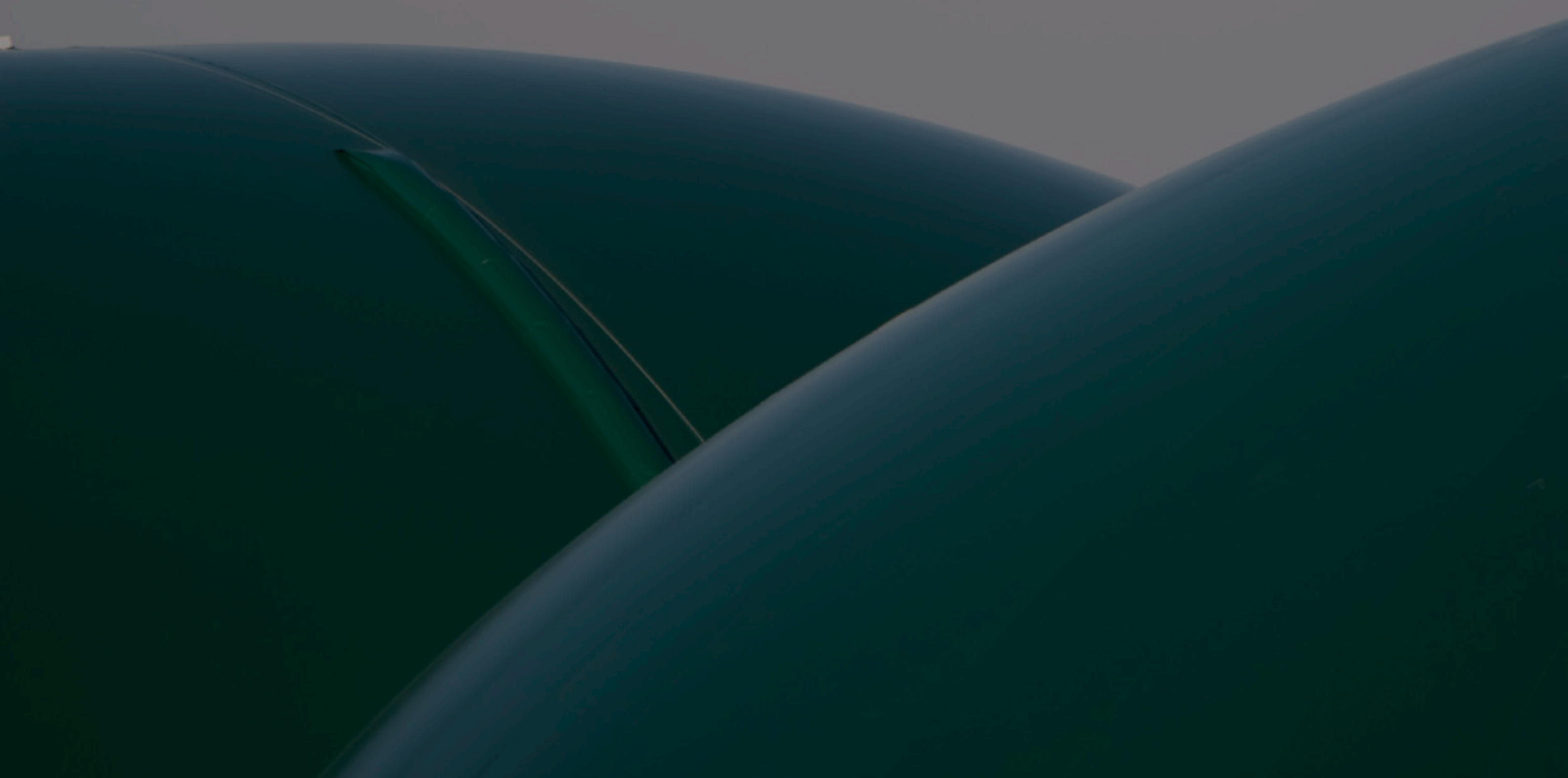
TRL maturity

- Liquid solvents – particularly amines - are among the most advanced solutions with a TRL 7-9 together with single membrane and solid adsorbent solutions.
- The TRL forecast illustrates that there is a broad range of capture technologies across all presented categories that can reach TRL 9 in 2030. This would require continuous and focused research and innovation for each technology.
- Maturing a broader variety of solutions yields potential for further specialisation of CO_2 capture solutions for targeted emitters to improve cost-efficiency. It is therefore crucial to research the different solutions' potential for highest capture efficiency per emitter type.
- Solutions with TRL 9 still require research and optimisation around the core capture technology like monitoring of gas flows and purities, which require continuous development and approval at a large-scale level.q

Determining factors for application

- Lifetime and CO_2 volumes of the emitter
- Remaining high energy penalty
- Demand for additional renewable energy
- Retrofitting capability for existing emitters

Negative emissions from CO_2 capture & storage



Negative emissions from CO_2 capture & storage

Negative emissions from capturing biological CO_2 play a crucial role in addressing climate change and achieving carbon neutrality. Negative emissions refer to the capture and storage of biogenic CO_2, which means that it leads to a direct removal of CO_2 from the atmosphere as opposed to an avoidance of additional emissions in the atmosphere, when capturing fossil CO_2. Achieving the Danish and European climate targets requires not only emission reductions but also negative emissions.

In this category, three different groups of negative emission technologies will be presented:

→ BECCS
→ DAC
→ Nature-based solutions

Biogenic carbon capture and storage (BECCS)

BECCS describes the capture and storage of biogenic CO_2 from point sources, whereas DAC and nature-based solutions capture CO_2 directly from the atmosphere. BECCS utilises biogenic sources, which encompass process emissions from biofuel and biohydrogen production, as well as combustion emissions from power plants, waste-to-energy facilities and industrial applications. These sources may involve biomass firing or co-firing in sectors such as cement, pulp and paper, or the utilisation of biochar as a reducing agent in steel production.[14] For BECCS, the same CO_2 capture solutions are applied as for CO_2 capture of fossil CO_2 from point sources.

For the large-scale application of BECCS it has to be considered that biomass represents a finite resource. Consequently, the process of carbon removal through biomass utilisation must be approached with an understanding of sustainable production from an environmental and biodiversity perspective.

While the readiness level of some BECCS solutions has reached commercial viability, the majority remain in the demonstration or pilot phase. CO_2 capture from first-generation bioethanol production stands out as the most mature BECCS route, while large-scale gasification of biomass for synthetic gas applications remains in the large prototype stage. In industrial settings, biomass co-firing has already attained commercial status in pulp and paper mills, cement plants and steel blast furnaces.

A notable large-scale project is the Midwest Carbon Express project in the US connecting 32 bioethanol plants over 5 states with a ~3000km pipeline.[15]

DAC

Direct Air Capture (DAC) is a special form of chemical CO_2 capture, where CO_2 is not derived from a point source, but extracted directly from the atmosphere. Generally, this involves employing extensive arrays of fans to draw air through a chemical carbon capture mechanism. The two most advanced DAC technologies for near to mid-term implementation, which overlap with some solutions for CO_2 capture from point sources, are:

→ Solid adsorption and low temperature regeneration.
→ Liquid absorption and high temperature regeneration.[16]

1,200,000 m^3 of air contain approx. 1 tonne of CO_2

Energy cost of ~6-10 GJ/ton of CO_2 captured.

DAC is currently an energy-intensive and thereby costly solution. The atmospheric CO_2 concentration amounts to ~0.04 volume percent and is thereby much lower than the concentrations in gas captured from conventional point sources which ranges between 10 and 25 volume percent*

*technology_data_for_carbon_capture_transport_and_storage.pdf (ens.dk)

14 Bioenergy with Carbon Capture and Storage - Energy System - IEA
15 Project Footprint - Summit Carbon Solutions
16 technology_data_for_carbon_capture_transport_and_storage.pdf (ens.dk)

Innovation and R&D potentials

Energy consumption: Low temperature DAC needs more development to reduce energy consumption and the geometrics of the air-contractor, which presents this technology with challenges for large scale application.

Desorption: High temperature DAC is easier to apply at scale. However, it applies calcination technology, where the desorption process costs a minimum of 4 MJ/kg.

Air contractor technology: Air contractor enhancements are crucial for improving DAC efficiency. Research efforts include refining designs to increase CO_2 capture rates while reducing energy consumption, particularly from fans. Innovations such as passive air contactors utilise natural wind, eliminating the need for mechanical fans with the potential to reduce costs for larger systems[17].

Solvent technology: Advancements in solvent technology focus on enhancing kinetics and efficiency to reduce costs and energy requirements in DAC. Research explores alternative materials like low-cost alkaline substances, Metal-Organic Frameworks (MOFs), and biologically enhanced mechanisms to streamline CO_2 capture and storage. Emerging solvent desorption methods, using electrical fields or bipolar membranes, are also being developed to minimise the energy needed for solvent regeneration[18].

Modularity and plant siting: This approach facilitates rapid scaling and leverages external supply chains, which could accelerate technological advancements and cost reductions. An advantage of DAC is its ability to capture CO_2 from a variety of locations, independent of emission from point sources. This enables placement close to renewable energy production, storage or utilisation sites to minimise transport costs. However, further research is needed to assess how location factors like weather conditions can impact the operation and capture efficiency of DAC.[19]

System integration: The efficiency of DAC can be increased through improved system integration. There are for instance research efforts looking into synergy exploitation between green hydrogen production and DAC for CO_2 utilisation projects. Green hydrogen production creates excess heat, which can be utilised for the operation of DAC facilities. The choice of location for the DAC facility close to other capture projects or renewable energy facilities can also improve the connection to evolving CO_2 infrastructure to minimise transport costs.

Cost reduction and scalability: The cost of DAC is very dependent on the source of renewable energy that is used. There are efforts to lower costs through modular technology and high-volume manufacturing within renewable energy supply and energy storage within the solar PV, wind and battery sector. These developments are crucial for making ESA more economically viable and scalable[20].

There is also emerging research into new capture techniques for DAC. In the following paragraph electro swing adsorption, zeolites and passive DAC will be presented:

Electro Swing Adsorption (ESA): This technology employs an electrochemical cell where solid electrodes adsorb CO_2 when negatively charged and release it when positively charged. This technology is noted for its ability to operate flexibly with various energy sources, which is vital for its integration into different energy systems[21].

> **Energy requirements and efficiency:** ESA's operation is energy-intensive, requiring about 2 terawatt hours per million tons of CO_2 captured[22]. The process involves continuous charging and discharging cycles. Initiatives in the US and UK are underway to transition ESA to operate fully on renewable energy, aiming to reduce energy consumption and environmental impact. Innovations include the potential use of industrial waste heat to power electrochemical reactions, enhancing energy efficiency.
>
> **Material durability and innovations:** The durability of ESA's electrodes is challenged by frequent cycling, which can degrade materials and increase maintenance costs. Research into more robust materials like graphene or carbon nanotubes is expected to improve conductivity and mechanical stability, extending the system's lifespan and reducing costs.

Zeolites: Utilised for their porous structure ideal for CO_2 adsorption, zeolites are central to ongoing DAC initiatives. The first operational DAC plant using zeolites was commissioned in Norway in 2022. The 'Removr' project plans to scale this technology to capture 2000 tons of CO_2 per year by 2025[23]. Research continues to improve the kinetics and mass transfer efficiency of zeolite-based processes, aiming to lower production costs and increase efficiency[24].

17 An effective air–liquid contactor for CO_2 direct air capture using aqueous solvents - ScienceDirect
18 A review on progress made in direct air capture of CO_2 - ScienceDirect
19 A review of direct air capture (DAC): scaling up commercial technologies and innovating for the future - IOPscience
20 Current status and pillars of direct air capture technologies - ScienceDirect
21 Direct Air Capture - Energy System - IEA
22 Faradaic electro-swing reactive adsorption for CO_2 capture - Energy & Environmental Science (RSC Publishing)
23 Direct Air Capture - Energy System - IEA
24 Utilization of zeolites as CO_2 capturing agents: Advances and future perspectives - ScienceDirect

Saturation and Regeneration: Zeolites can quickly become saturated with CO_2, necessitating frequent regeneration which can be energy intensive. Improving the regeneration efficiency while maintaining the integrity of the zeolite structure is challenging[25].

Selectivity and Efficiency: While zeolites are good at adsorbing CO_2, they also trap other gases, which can reduce their overall efficiency and selectivity for CO_2 capture[26].

Advanced Porous Materials: Development of zeolites with tailored pore sizes and surface chemistries could enhance selectivity and capacity for CO_2. This customisation would allow for more targeted capture of CO_2, potentially improving the efficiency of the DAC process[27].

Scalable Manufacturing: Innovations in the synthesis of zeolites could lead to more cost-effective and scalable production processes. This would make the use of zeolites more economically viable for large-scale DAC operations[28].

Passive DAC: Leveraging natural processes, this technology converts calcium hydroxide into limestone by capturing atmospheric CO_2. Innovations in passive DAC focus e.g. on using renewable energy-powered kilns to enhance the efficiency of this conversion process. Passive air contactors, which use natural wind and convective flows instead of mechanical fans, are under investigation to reduce operational costs and energy requirements.

Rate of capture: Passive DAC generally has lower CO_2 capture rates compared to active systems that use fans or blowers. Increasing the capture rate without resorting to energy-intensive methods remains a significant challenge[29].

Dependency on Environmental Conditions: The efficiency of passive DAC systems is highly dependent on local climatic conditions, such as humidity and wind speed, which can vary widely and affect performance unpredictably[30].

Design improvements: Innovations in the design of passive DAC systems, such as increasing the surface area for CO_2 absorption and optimising materials for better interaction with CO_2, could significantly improve their efficiency[31].

Hybrid systems: Combining passive DAC with active components could strike a balance between energy use and capture efficiency. For instance, passive systems could be used during periods of optimal weather conditions, while active systems could boost CO_2 capture when environmental conditions are not favourable[32].

There are several DAC initiatives under development and implementation worldwide. An example is the U.S. Regional Direct Air Capture Hubs program, managed by the Office of Clean Energy Demonstrations. The programme is set to establish four DAC hubs designed to capture at least 1 Mt of CO_2 annually from the atmosphere. The project is funded by $3.5 billion from the Bipartisan Infrastructure Law and provides funding for the project over five years (2022-2026).[33]

Another commercial scale DAC project is running in Iceland. In 2021, the Orca project was launched as the biggest DAC project at that time with a technical capacity of capturing 4,000 tons of CO_2 yearly, equivalent to the emissions of 800 cars. The facility stores the CO_2 underground in Iceland through mineralisation. An additional project called Mammoth is under implementation in the same area as Orca, having approximately ten times the size of Orca, aiming to capture up to 36,000 tons of CO_2 annually. The ultimate ambition is to expand further, targeting a multi-megaton capacity by the 2030s, with the ultimate goal of achieving gigaton capacity by 2050.[34]

The land required to deploy DAC is estimated to 0.2 km² per Mt of CO_2 removal. This is significantly smaller than the required area for e.g. nature-based solutions.[35]

25 Zeolites as Selective Adsorbents for CO_2 Separation | ACS Applied Energy Materials
26 Zeolites as Selective Adsorbents for CO_2 Separation | ACS Applied Energy Materials
27 A review on recent developments in Zeolite A synthesis for improved carbon dioxide capture: Implications for the water-energy nexus - ScienceDirect
28 Synthesis of zeolites from low-cost feeds and its sustainable environmental applications - ScienceDirect
29 https://www.sciencedirect.com/science/article/pii/S2589004222002607
30 The impact of climate on solvent-based direct air capture systems - ScienceDirect
31 The impact of climate on solvent-based direct air capture systems - ScienceDirect
32 Harnessing Wind with a Passive Direct Air Capture (PDAC) System for CO_2 Capture: Insights from Computational Fluid Dynamics Modeling | Industrial & Engineering Chemistry Research (acs.org)
33 Regional Direct Air Capture Hubs | Department of Energy
34 World's largest direct air capture project - Ramboll Group
35 Current status and pillars of direct air capture technologies - ScienceDirect

Current TRL for DAC

Figure 11 illustrates the current TRL of DAC which is estimated to a level of 6. This is an overarching estimation for DAC technology. The TRL of specific DAC solutions might vary.

Figure 11: TRL for DAC

Technology	TRL	1	2	3	4	5	6	7	8	9
DAC										

TRL forecast for DAC

Figure 12 provides a forecast on the estimated time period that it would take DAC to reach TRL 9 assuming a regular TRL development time with continuous research efforts.

Figure 12: TRL forecast for DAC

Technology	Status 2024	2030	2035	2040	2045	2050
Direct Air Capture	6	9				

Conclusions

→ Main challenges for DAC remain large consumption of electricity, sufficient capture rates and technology application at large scale.
→ DAC is independent from CO_2 point sources and can thereby be placed close to renewable energy sources, utilisation or storage facilities to increase efficiency. Another factor for the positioning of DAC can be the integration into existing CO_2 infrastructure for point sources.
→ Further research is needed to assess how location factors are affecting the operation and efficiency of DAC.
→ Concrete targets or economic incentives for DAC technology could spur a faster technology development of DAC.
→ International sparing on DAC technology, geographical influences and upscaling should be enhanced to evaluate contribution potential from research in a Danish perspective.

TRL maturity

→ At the current TRL 6, DAC technology is estimated to be available for large scale application in 2030.
→ If DAC should contribute to reaching the 2030 climate targets, more focused research into DAC and a higher number of DAC projects would be required to push DAC to TRL 9 before 2030.[36]

Determining factors for application

→ High demand for additional renewable energy.
→ Price of the renewable energy used for DAC.
→ The capture efficiency of DAC facilities.
→ Potential competition with PtX-solutions like hydrogen production for sufficient renewable energy supply.
→ Dedicated space to the placement of DAC facilities.

Nature-based solutions

Natural biological systems capture CO_2 by photosynthesis and storage in biomass. The storage is strongly affected by land management options such as plant selection, soil and crop management and the end use of the biomass produced. Nature-based solutions (NbS) refer to the atmospheric capture and storing of CO_2 in plants and soils, e.g., through strategies like afforestation, wetland restoration and sustainable agriculture practices. Some nature-based solutions, such as conserving existing wetlands, serve mainly to prevent greenhouse gas emissions. Others, such as restorative agriculture and regrowing forests, actively remove CO_2 from the atmosphere. Oceans and forests serve as key natural carbon sinks, directly capturing CO_2 from the atmosphere through processes inherent in ecosystems, thus effectively reducing atmospheric carbon levels. Potentials in increasing and strengthening contributions from biomass storage

36 Refer to the chapter on CCUS reduction pathways to learn more about DAC capture potentials in 2030 and 2050.

to the 2030 and 2050 targets in Denmark are significant and include both increased carbon uptake (additionality) and stabilisation of carbon stored in terrestrial and marine eco-systems (permanence).

Achieving net-zero emissions by 2050 necessitates both rapid decarbonisation and significant land-based contributions, with NbSs playing a crucial role through protection, restoration and sustainable management of natural carbon sinks and reservoirs.

Forests

Forests and harvested wood products play a crucial role in capturing CO_2. As trees grow, they absorb atmospheric CO_2 and thereby store carbon in the wood mass. The carbon remains stored in the wood after trees are cut and processed into wood products. When wood deteriorates or is burned, the stored carbon is released back into the atmosphere as CO_2. Carbon storage in trees is thereby temporary and varies based on factors like tree age and the lifespan of wood products before disposal and burning.[37]

Emission reductions through forests is determined by environmental factors like available area, the growth time of a tree and the natural CO_2 capture capacity of a tree. These factors can vary by species. The preconditions for the application of forestation for carbon capture are therefore very different from technical/chemical capture solutions from e.g. CO_2 point sources.

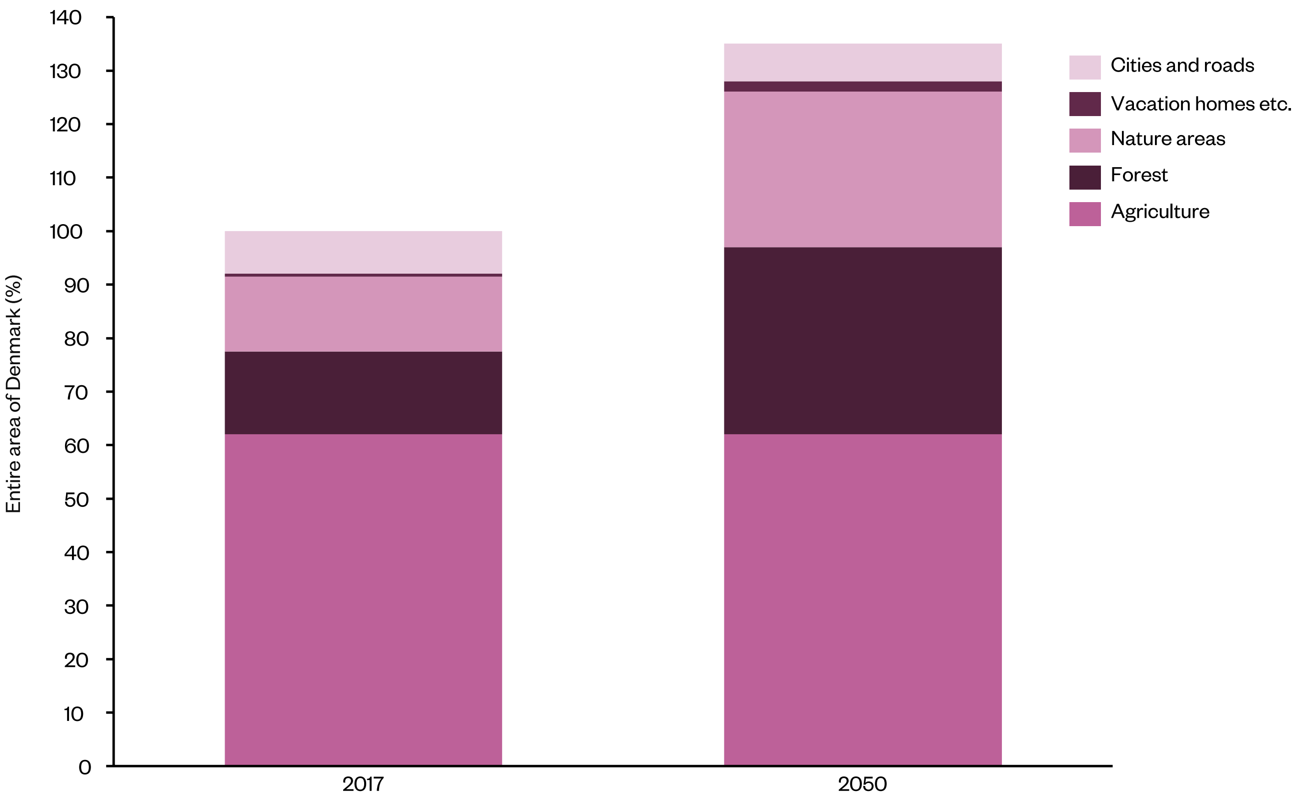
The total Danish land area is estimated to 4.3 million hectares. Currently, 2.6 million hectares are dedicated to agricultural use, while the remaining 1.7 million hectares consist of forests, urban areas, and natural landscapes.* In the Danish climate status & outlook, forest area is assumed to grow from ~650,000 hectare to ~680,000 hectare in 2030.**

* Det Biogene Kulstof_web.pdf (foodbiocluster.dk)
** KF24 Kapitel 19 Skov og høstede træprodukter.

Looking ahead to 2030 and 2050, the interaction between agricultural and forest/nature areas becomes crucial in assessing the potential for emission reductions through forest management and afforestation. Afforestation typically involves expanding forest areas, which would consequently reduce the available land for agriculture. This roadmap is focusing on the potentials of afforestation and reforestation.

Figure 12B illustrates area requirements based on assumptions and scenarios of the Danish Board of Technology from 2017. The graph illustrates the dilemma of increased area requirements for forests/nature, when keeping the agricultural land use at a steady level.[38]

Figure 12B: Area requirements based on Danish Board of Technology assumptions



37 KF24 Kapitel 19 Skov og høstede træprodukter.pdf (kefm.dk)
38 Det Biogene Kulstof_web.pdf (foodbiocluster.dk)

Since 1990, forests have consistently absorbed more carbon than harvested. While both the Danish climate status & outlook 2024 and 2023 anticipate declining absorption over the next five years, the decline in the Danish climate status & outlook 2024 is expected to be less evident. The 2023 projection assumed a stable absorption of approximately ~0.3 million tons of CO_2 equivalent by 2030, whereas the 2024 forecast assumes a stable absorption level of around ~1.8 million tons by the same year. The difference in projections between 2023 and 2024 arises from the use of different forest projection models. The 2023 projection relied on the previous model, which proved inconsistent with actual forest data. The new model is expected to better reflect real forest development.

For every hectare of forest that is planted, an average of approx. 11 tons of CO_2 annually is captured, corresponding to the emissions of approx. 2 Danes.* A 100-year-old large tree in the forest (diameter of 50 cm and a height of 32 m) binds ~4.3 tons of CO_2.

* Skovene bidrager positivt til CO_2-balancen! - Dansk Skovforening

Innovation and R&D

Reforestation and afforestation: This process aims to restore or increase forest areas, absorbing CO_2 from the atmosphere. Reforestation involves replanting trees in previously cleared areas, while afforestation creates new forests on historically non-forested lands. These practices sequester carbon, enhance biodiversity, and regulate hydrological cycles, aiding climate change mitigation and adaptation[39].

Biomass growth & storage potential: Afforestation and forest management to improve the productivity of forests requiring research into increasing biomass growth, carbon sequestration and carbon storage per area in agri- and aquaculture production through species selection, genetics and management. This includes assessment of long-term carbon storage in biosystems under different growth conditions and future climates.

Species selection and technological integration: Identifying and cultivating tree species that excel in carbon sequestration and adaptability is crucial. Integrating genetic engineering enhances species' resilience, while employing drone planting and remote sensing ensures precise ecosystem monitoring and maintenance.

Regional focus and climatic adaptations: Afforestation and reforestation require research to assess their effectiveness under various climatic conditions. Studies focus on tree gas exchanges and land-use change effects on albedo, crucial for understanding forestry cover's climatic impacts[40].

Enhancing carbon sequestration techniques: Advancements in carbon sequestration methods are essential, alongside climate modelling improvements to better comprehend forestry activities' climate interactions. Enhancements in monitoring, data analytics and innovative planting techniques, coupled with increased community engagement, ensure the scalability and effectiveness of reforestation efforts[41].

Soil carbon sequestration: This process uses land management and agricultural practices to boost soil carbon storage. Techniques like no-till farming, cover cropping and organic amendments like compost improve soil health and productivity while capturing CO_2 and reducing greenhouse gases[42].

Advanced research and organic amendments: There is need for research into soil microbiomes enhances natural carbon storage processes. Development of new and improved carbon-rich organic amendments increases these methods' efficacy and sustainability, boosting soil carbon storage capacities[43].

Measurement challenges and technological advances: Significant challenges in measuring carbon sequestration and managing greenhouse gas emissions persist. Research focuses on understanding soil gas fluxes and developing rapid, accurate measurement techniques, with innovations in remote imaging and regenerative agriculture enhancing soil carbon monitoring and scalability[44].

39 https://climate-adapt.eea.europa.eu/en/metadata/adaptation-options/afforestation-and-reforestation-as-adaptation-opportunity
40 https://www.researchgate.net/publication/216814292_Integration_of_albedo_effects_caused_by_land_use_change_into_the_climate_balance_
41 https://www.researchgate.net/publication/216814292_Integration_of_albedo_effects_caused_by_land_use_change_into_the_climate_balance
42 https://www.mdpi.com/2673-4133/4/3/36
43 https://www.sciencedirect.com/science/article/pii/S0959652623021510
44 Fact Sheet: Soil Carbon Sequestration | American University, Washington, DC

Education for wider adoption: Educational programmes and training bridge knowledge gaps and facilitate widespread adoption of these practices within the farming community, amplifying soil carbon sequestration efforts' impact[45].

Biochar: Biochar is a carbon-rich form of charcoal produced by heating biomass, like agricultural residues, without oxygen. The process is called pyrolysis.[46] Biochar can be added to soil to enhance fertility and boost carbon content for long-term carbon sequestration[47].

1 tonne biochar is estimated to store 2 tons CO2e.*
Pyrolysis of 4 tons of straw produce ~1 tonne of biochar.**

* Vejen-til-effektiv-CO2-lagring-med-biokul-CIP-Fonden-januar-2024.pdf (cipfonden.dk)
** Skyclean-direktør: Der er plads i marken til CO2-fangst og lagring med biokul i stor skala (LandbrugsAvisen)

Efficiency: The effectiveness of biochar varies due to different biomass types and pyrolysis conditions, highlighting the need for research to tailor biochar to specific soil and climatic conditions[48][49]. Research is looking into optimising the pyrolysis process to increase the yield and quality of biochar, while reducing energy inputs and emissions from soils and improving water retention.

Technological and lifecycle analysis: Research is ongoing to optimise biochar's properties and assess its lifecycle impacts, from production to disposal. This includes exploring sustainable feedstock sources and mitigating environmental drawbacks[50].

Agriculture integration: Enhancing connections with farmers and stakeholders is crucial. Advances in particle size optimisation and activation methods are needed to scale biochar use effectively as a soil amendment[51].

Enhanced rock weathering: This method involves spreading finely ground silicate rocks like basalt to react with CO_2 and stabilise it as minerals. This enriches soils and may boost agricultural productivity while reducing reliance on synthetic fertilisers[52][53]. The US company Lithos has successfully deployed 11,000 tons of basalt for CO_2 capture in 2022.[54]

Tests in Greenland have indicated that 1 tonne of glacial rock flour can absorb between 250 and 300 kilogrammes of CO2 when applied to fields*

* Greenland's Glacial Rock Flour offers a solution to regenerative agriculture (ksapa.org)

Reduction potentials: The carbon reduction potential of rock weathering is under study, with significant regional variations noted. The dual role of agriculture as an emitter and a carbon sink warrants further exploration.

Challenges and technological development: Scaling rock weathering requires cost management and minimal environmental impacts. Innovations in large-scale mineral extraction and distribution machinery are needed, along with international regulatory cooperation.

Environmental and social impact: Rock weathering consumes considerable energy and can adversely affect soil health and crop yields. It may also pose risks to vulnerable communities. Developing strategies to mitigate these risks is vital[55][56].

45 https://ec.europa.eu/info/funding-tenders/opportunities/docs/2021-2027/horizon/wp-call/2023-2024/wp-9-food-bioeconomy-natural-resources-agriculture-and-environment_horizon-2023-2024_en.pdf
46 Carbon dioxide removal (europa.eu)
47 Application of biochar in agriculture and environment, and its safety issues | Biomass Conversion and Biorefinery (springer.com)
48 J. Samaniego and others, "Nature-based solutions and carbon dioxide removal", Project Documents (LC/TS.2022/224), Santiago, Economic Commission for Latin America and the Caribbean (ECLAC), 2023
49 https://www.mdpi.com/2311-5629/9/3/67
50 https://www.technologynetworks.com/immunology/news/new-map-shows-which-countries-have-the-most-biochar-to-capture-carbon-380795
51 https://news.cornell.edu/stories/2023/11/maps-reveal-biochars-potential-mitigating-climate-change
52 Frontiers | CO_2 Removal With Enhanced Weathering and Ocean Alkalinity Enhancement: Potential Risks and Co-benefits for Marine Pelagic Ecosystems (frontiersin.org)
53 The state of carbon dioxide removal (squarespace.com)
54 Introducing Lithos: Carbon removal using the power of enhanced rock weathering (substack.com)
55 Enhanced Rock Weathering | MIT Climate Portal
56 Enhanced Weathering: Using Rocks to Address Climate Change - The Conservation Foundation

Wetland and peatland: These ecosystems are key carbon sinks. Innovative hydrology and vegetation restoration techniques are essential for their conservation and carbon sequestration capabilities.

Restoration: Restoring wetlands and peatlands is financially intensive and technically challenging, especially when addressing land use conflicts. Balancing ecological and economic needs is critical[57].

Methane (CH_4) management: Current research aims to reduce and capture methane emissions. This will require innovative restoration techniques and cost-effective monitoring tools [58]. Approaches, such as selecting appropriate plant species and optimising wetland design, are being explored to enhance CH_4 oxidation and reduce emissions. Development of cost-effective tools is underway to accurately measure CH_4 fluxes, enabling better management and control of greenhouse gas emissions from wetlands. Research aims to integrate these advancements into sustainable wastewater treatment systems.

Monitoring: There is a general need to accurately monitor, model and forecast carbon sequestration and storage in ecosystems, carbon recyclability in products and use of biomass products critical to climate accounting. Effective monitoring systems are crucial for evaluating the success of restoration efforts and their impact on climate mitigation. Focus areas include hydrology management, carbon sequestration efficiency, and resilience to climate change and fires[59][60][61][62].

Biodiversity & environment: Biomass being a scarce resource, it is important to ensure that intensive biomass use does not compromise biodiversity and other environmental issues and to generally understand societal value of ecosystem services. Significant biomass production requires moreover improved spatial planning to ensure holistic planning and application of NbSs.

There is a bigger variety of NbSs than considered in this analysis especially around carbon sequestration solutions for oceans. However, many of these solutions have a TRL below 3. As these solutions reach higher TRLs, they should be considered in research efforts as Denmark has marine area available, which can be used for additional emission reduction efforts.

The application of NbSs is not only dependent on the TRL but also on the assessment of their actual reduction potentials and at the same time required space for application to reach targeted emission reductions. This requires efficient area planning as some technologies are compatible with e.g. agricultural practices, while others might be competing for space.

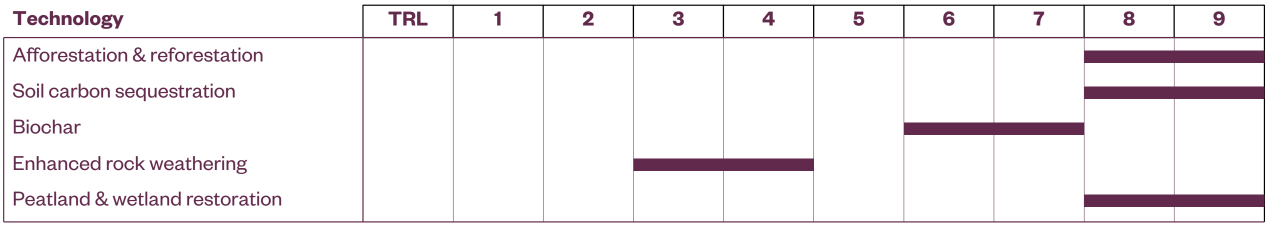
Another limiting factor for achieving negative emissions through biogenic CO_2 are the available volumes of biomass and potentials for its production increase. This will be further discussed in the chapter on CO_2 utilisation solutions.

57 Review of carbon dioxide utilization technologies and their potential for industrial application - ScienceDirect
58 https://www.ncbi.nlm.nih.gov/pmc/articles/PMC9936987/
59 Peatlands and climate change - resource | IUCN
60 J. Samaniego and others, "Nature-based solutions and carbon dioxide removal", Project Documents (LC/TS.2022/224), Santiago, Economic Commission for Latin America and the Caribbean (ECLAC), 2023
61 https://news.mongabay.com/2023/02/peatland-restoration-in-temperate-nations-could-be-carbon-storage-bonanza/
62 https://news.ucsc.edu/2021/12/wetlands-restoration.html

Current TRL for nature-based solutions

Figure 13 provides an overview of TRLs for selected NbSs published by an international research collaboration on carbon dioxide removals led by the University of Oxford.

Figure 13: TRL for nature-based solutions



Forecasted TRL for nature-based solutions

Figure 14 provides a forecast on the estimated time period needed for the presented NbSs to reach TRL 9 assuming a regular TRL development with continuous research efforts for each technology.

Figure 14: TRL forecast for nature-based solutions

Technology	Status 2024	2030	2035	2040	2045	2050
Afforestation & reforestation	8-9					
Soil carbon sequestration	8-9					
Biochar	6-7	9				
Enhanced rock weathering	3-4		9			
Peatland & wetland restoration	8-9					

Conclusions

- The assessment of reduction potentials and timespan of sequestration remain important research demands for NbSs.
- An important factor for the application of NbSs is the available area for application and the availability of biomass.
- A better understanding of the interplay of NbSs with the agricultural sector is required to assess how the solutions can be integrated in established agricultural practices. This will be an important factor for an accelerated application of the solutions.

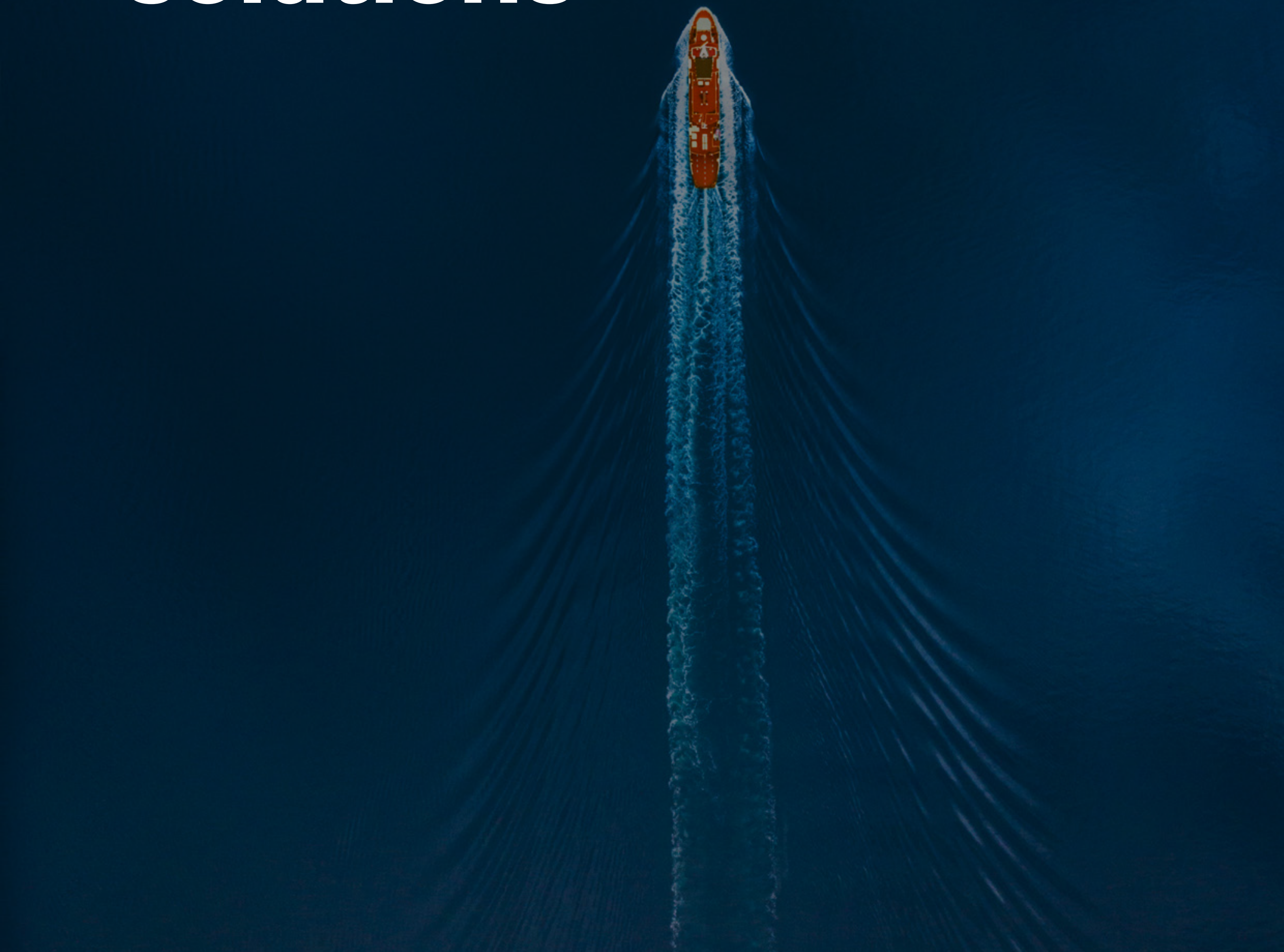
TRL maturity:

- Most of the considered NbSs have a high TRL between 8-9. Newly developed solutions like biochar (TRL 6-7) and enhanced rock-weathering (TRL 3-4) are lacking slightly behind.
- Biochar is expected to be ready for large scale application in 2030, while it takes enhanced rock weathering until 2035 to mature to TRL 9. Reaching a TRL development at this speed does require intensive, continuous research and innovation.
- The application of other presented solution with high TRL – like afforestation - require more research into e.g. time horizons for tree growth up to full capture capacity and space for application. There is also need for research into how to balance reduction demands from forests with biomass demands.

Determining factors for application

- The application of NbSs requires significant space, which is in potential competition with agricultural food production. Some of the practices can be synced with agriculture.
- Environmental boundaries for nature and biodiversity.
- Available biomass volumes and potentials for their increase.

CO_2 transport solutions



CO_2 transport solutions

The most relevant modes of transport for CO_2 are pipeline, ship, rail and truck. Beyond the actual transport vehicle, there are also other steps involved in the infrastructure planning like compressor stations and the role of harbours for receival and export of CO_2.

The transport of CO_2 is a central part of the CCS and CCU value chain. The lack of joint CO_2 infrastructure for onshore and offshore storage is a main bottleneck to establish the CCUS industry at national and EU level. In Denmark, several initiatives have been established around developing a CO_2 backbone infrastructure at regional and national level. The Danish government had commissioned five regional infrastructure clusters to assess options for joint infrastructure development and best possible utilisation of synergies between emitters, storage operators and utilisation projects. Main challenges for establishing a joint backbone are the dimensioning of infrastructure without having full value chain projects in place and the levelling of CO_2 streams from different emitters in terms of pressure and purity.

Key parameters to consider for establishing CO_2 infrastructure

Assessment Parameters

• State of transport: Liquid, supercritical, gaseous • Transport parameters: pressure, temperature • Feasible transport distances • Loading, unloading facilities • Infrastructure dimension: sizing of pipe, ship, truck	• CAPEX (class V) • OPEX (class V) • CO_2 volumes • Tariff structures • Timeline for establishment/ delivery of infrastructure • Loading, unloading times • Additional costs: e.g. harbour, compression, liquefaction	• Ownership models for infrastructure • Consideration of CO_2 ownership along the value chain • National plans/strategies for infrastructure backbone • Consideration of potential transport routes • Construction permits	• Environmental permits • Environmental impact • Waste production • Public acceptance • Social impacts

Innovation and R&D

The conveyance of gases and liquids through pipelines, shipping, truck and rail is well-established. However, the transportation of CO_2 at large scale required for CCUS has not been accomplished in a European context for several transportation methods.

Large scale shipping & retrofitting: Shipping of liquid gases like LNG is a well-developed technology and parameters for loading liquid CO_2 instead are known as well. However, specific designs for dedicated CO_2 ships and for large scale shipping of CO_2 is still to be tested. It is also relevant to investigate the construction of CO_2 ships vs. retrofitting of containerships carrying CO_2 containers.[63] The retrofitting of existing ships has been applied in the Greensand project to be able to kick start the CO_2 storage faster. It must be investigated, if this solution is also feasible for large CO_2 volumes. Moreover, research into solutions for ships to dock CO_2 storage facilities is required. The same lack of large-scale demonstration is lacking for rail transport of CO_2.

I**Large scale CO_2 pipelines & retrofitting**: CO_2 transport via pipelines is facing the same challenge as ships in the sense that there is little experience with long distance CO_2 pipeline infrastructure in Europe and no pipelines with CCUS purpose are established in Denmark. In the US, long distance pipelines for CO_2 have been in use for years mainly for the purpose of EOR. More than 8,000 kilometres of pipelines span across the United States.

63 Analyse+af+transport+af+og+infrastruktur+for+CO_2+8.+september.pdf (squarespace.com)

The Alberta Carbon Trunk Line (ACTL) is a prominent CCS initiative in Canada, noted as the world's largest CCS project. The project incorporates gasification, CO_2 capture, transportation, storage and enhanced oil recovery processes. It features 240km pipeline transporting up to 14.6 million tons of CO_2 annually from Alberta's Industrial Heartland to depleted oil fields in central and southern Alberta for enhanced oil recovery. The project received about $30 million from the Government of Canada's Clean Energy Fund and an additional $33 million from the ecoENERGY Technology Initiative. Completed between 2018 and 2020, the ACTL project cost an estimated $1.2 billion and spans multiple municipalities including Chipman and Lamont County[64]. Beyond the US, CO_2 pipelines are operational in Brazil, China, Canada, the Netherlands, and Norway. Notably, Norway is home to an offshore CO_2 pipeline, spanning 153 kilometres, serving the Snøhvit CO_2 storage facility.[65]

More investigation of existing infrastructure connections is needed to assess, where the repurposing of old gas pipelines can be used for CO_2 infrastructure. This can lead to considerable costs savings and less construction work compared to the establishment of new pipes. The Bifrost project is looking into the repurposing of an existing gas pipeline in the North Sea to the Harald field.[66] The same investigations are needed for the retrofitting of onshore pipelines.

Harbour infrastructure: Harbour infrastructure in general must be updated for CO_2 receival and export. This also requires the development and integration of new transportation arms on CO_2 ships that can connect to the CO_2 infrastructure of the storage sites or the harbour infrastructure. Interconnections between harbours, ships and pipelines have to be better understood. Harbours will play a crucial role in the reception and export of CO_2. They are also seen suitable for the placement of compressor stations to adjust pressure levels of incoming and outgoing CO_2. This will also require unified pressure and purity standards, which is being further elaborated in the chapter on societal coupling.[67]

Green Port Scandinavia at the Port of Hirtshals is an example for a large-scale CO_2 infrastructure and storage project aiming at establishing a European CO_2 hub with a goal for operation start in 2025-2026.[68]

Intermediate storage: Solutions for intermediate storage onshore and offshore need further investigation. One example for intermediate storage in harbours or nearshore are barges, which are flexible, floating intermediate storage components with tanks for liquid CO_2. This storage model is investigated by the CarbonCuts project but needs further knowledge and data gathering in different settings.[69] For intermediate storage solutions there is also a need for separate environment & safety assessments.[70]

Impurities: All captured CO_2 contains a certain level of impurity like NOx or H_2O, which can lead to corrosive compounds that can affect pipelines, compressors or wellheads. A better understanding of corrosion factors for different emitters and reactions with building materials like steel is essential to secure safe maintenance of the CCUS value chain over several decades.[71]

Rail transport: In a Danish context, relatively little attention is being paid to CO_2 transport on rail. It yields potentials for import from countries like Germany or Sweden with large emitters and a well-developed rail infrastructure network. It would require comparative analyses to assess the highest cost-efficiency of different transport modes with specific focus on import of foreign CO_2.

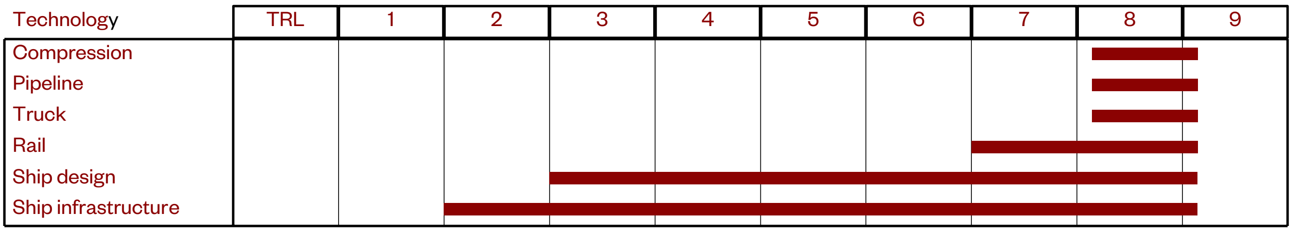
DB Cargo Scandinavia has announced the operation of an intermodal test train in Hirtshals as part of a pilot project to demonstrate the feasibility of rail freight connections for H_2 and CO_2 between Norway and continental Europe.[72]

64 Alberta Carbon Trunk Line - Alberta Major Projects
65 Technology-Readiness-and-Costs-for-CCS-2021-1.pdf (globalccsinstitute.com)
66 State-of-CCUS-onlineudgave.pdf (inno-ccus.dk)
67 Expert interviews
68 Northern Europe's largest CO_2 hub at Port of Hirtshals takes a significant step forward with support of 109 million DKK from the foundation. | Port of Hirtshals
69 State-of-CCUS-onlineudgave.pdf (inno-ccus.dk)
70 Expert interviews
71 PowerPoint-præsentation (squarespace.com)
72 The port of Hirtshals, Nordjyske railroads, and DB Cargo cooperate to shift cargo from road to rail – ShortSeaShipping

Current TRL for CO_2 transport solutions

Figure 15 provides an overview of TRLs for CO_2 transport solutions assessed by the Global CCS Institute.

Figure 15: TRL for CO_2 transport solutions



[73] Note: The TRL for CO_2 shipping varies between 3 and 9. At the lowest level, TRL-3, it involves offshore injection of CO_2 into a geological storage site from a ship. Conversely, *TRL-9 covers conventional onshore CO_2 injection from onshore facilities, with the possibility of transportation to the injection site via ship.*

Forecast of TRL development

Figure 16 provides a forecast on the estimated time period needed for the presented CO_2 transport solutions to reach TRL 9 assuming a regular TRL development time with continuous research efforts for each technology.

Figure 16: TRL forecast for CO_2 transport solutions

Technology	2024	2030	2035	2040	2045	2050
Compression	7-9*	9				
Pipeline	7-9*	9				
Truck	7-9*	9				
Rail	7-9	9				
Ship design	3-9	9				
Ship infrastructure	2-9	9				

**In a Danish context, pipelines, trucks and compression are assumed to have a TRL 7-9 instead of the presented TRL of 8-9 by the Global CCS Institute. Several full value chain projects with truck, pipeline and shipping infrastructure are expected to be implemented up to 2030 in Denmark.*

73 Technology-Readiness-and-Costs-for-CCS-2021-1.pdf (globalccsinstitute.com)

Conclusions

- In general, the conveyance of gases and liquids through pipelines, shipping, truck and rail is well-understood. In a Danish context, CO_2 transport solutions are lacking application and testing at large scale.
- Missing CO_2 infrastructure can constitute a substantial bottleneck for the implementation of CCUS projects.
- An important factor for CO_2 transport planning and further research is the dimensioning and purities of CO_2 infrastructure especially for ships and pipelines.
- There is a need for more research in connecting points for CO_2 transport between different parts of the value chain like the extension of harbours or the connection of ships to storage sites.
- Ships and pipeline have the biggest need for a fast maturing to TRL 9 as they will be applied in a large share of projects and are crucial modes of transport for the establishment of a national infrastructure backbone.
- Potentials of rail transport for the import of CO_2 from neighbouring countries should be assessed.

TRL maturity

- All presented transport solutions have the potential to reach TRL 9 in 2030 in a Danish context, if continues research and large-scale testing in projects is secured.
- CO_2 pipelines have a high TRL maturity building on know-how from implemented CO_2 infrastructure at a global level.
- Regarding shipping, the transport of gases is well-understood. Building of large-scale ships and the actual shipping of CO_2 in large volumes still has to be demonstrated. This results in a large span for the TRL estimation for ships.

Determining factors for application

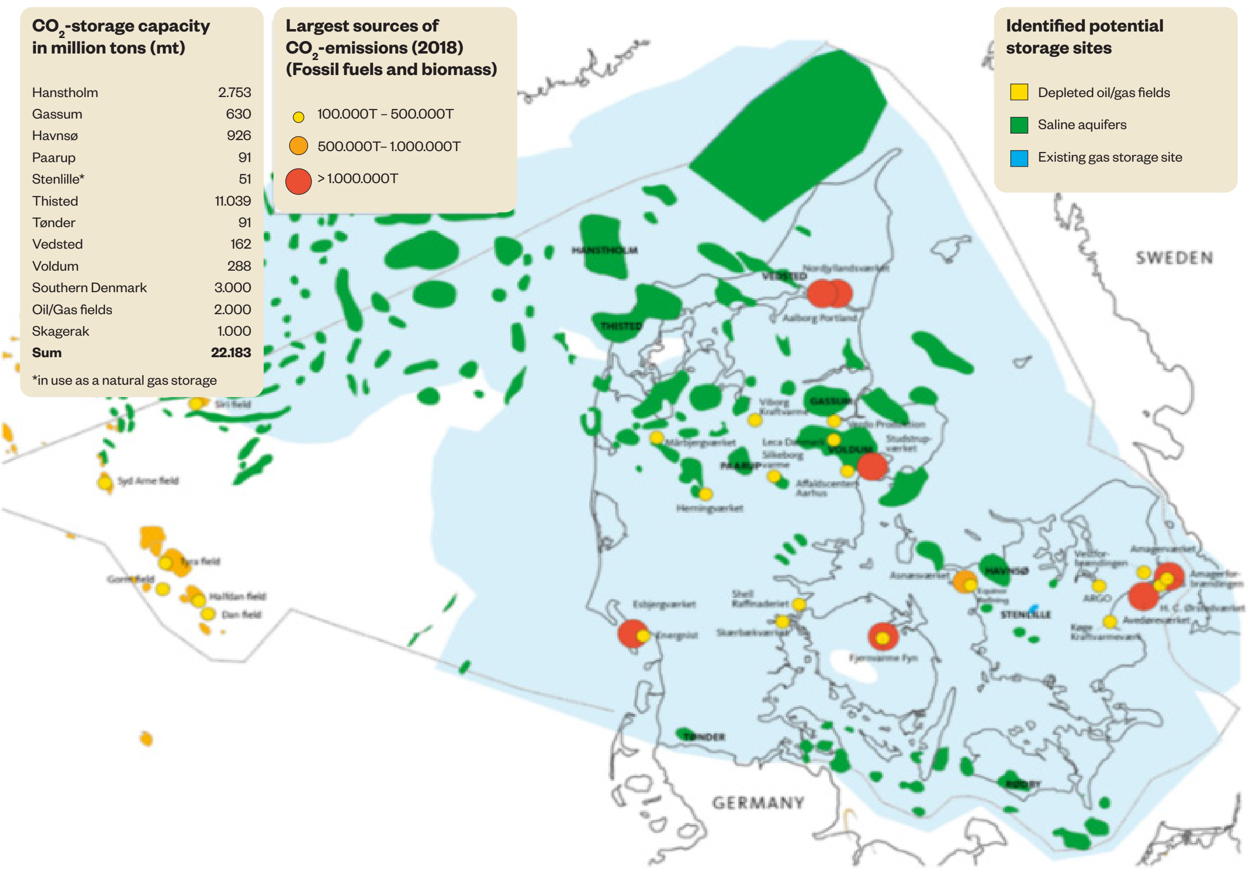
- Missing national and EU infrastructure backbone
- London protocol for transfer of CO_2 across borders
- Environmental regulation
- CO_2 purity and dimensioning

Geological CO_2 storage

Geological CO_2 storage

According to estimates by the National Geological Surveys for Denmark and Greenland (GEUS), the underground reservoirs of Denmark provide a substantial theoretical storage potential for CO_2, ranging between 12 and 22 billion tons of storage capacity. This exceeds Denmark's current annual CO_2 emissions by a factor of 400 to 700 making it relevant not only for storing Danish emissions but also to act as a storage hub for Northern Europe.[74]

Figure 17: Potential storage sites and main point source emitters in Denmark
Source: Innomission CCUS roadmap Vol. 1



In Denmark, the primary storage locations for CO_2 are anticipated to be porous and permeable sandstone layers, covered by one or more layers of sealing claystone. There are several different storage options available in Denmark, which should be examined to ensure that the right solutions are chosen on a national basis:

1. Offshore storage in hydrocarbon depleted sandstone fields
2. Offshore storage in hydrocarbon depleted chalk fields
3. Offshore storage in saline aquifers, (sandstone as well as chalk reservoirs with no hydrocarbons)
4. And near-shore and onshore storage in saline aquifers, such as existing gas storage sites.

74 Source Om CCS | Energistyrelsen (ens.dk)

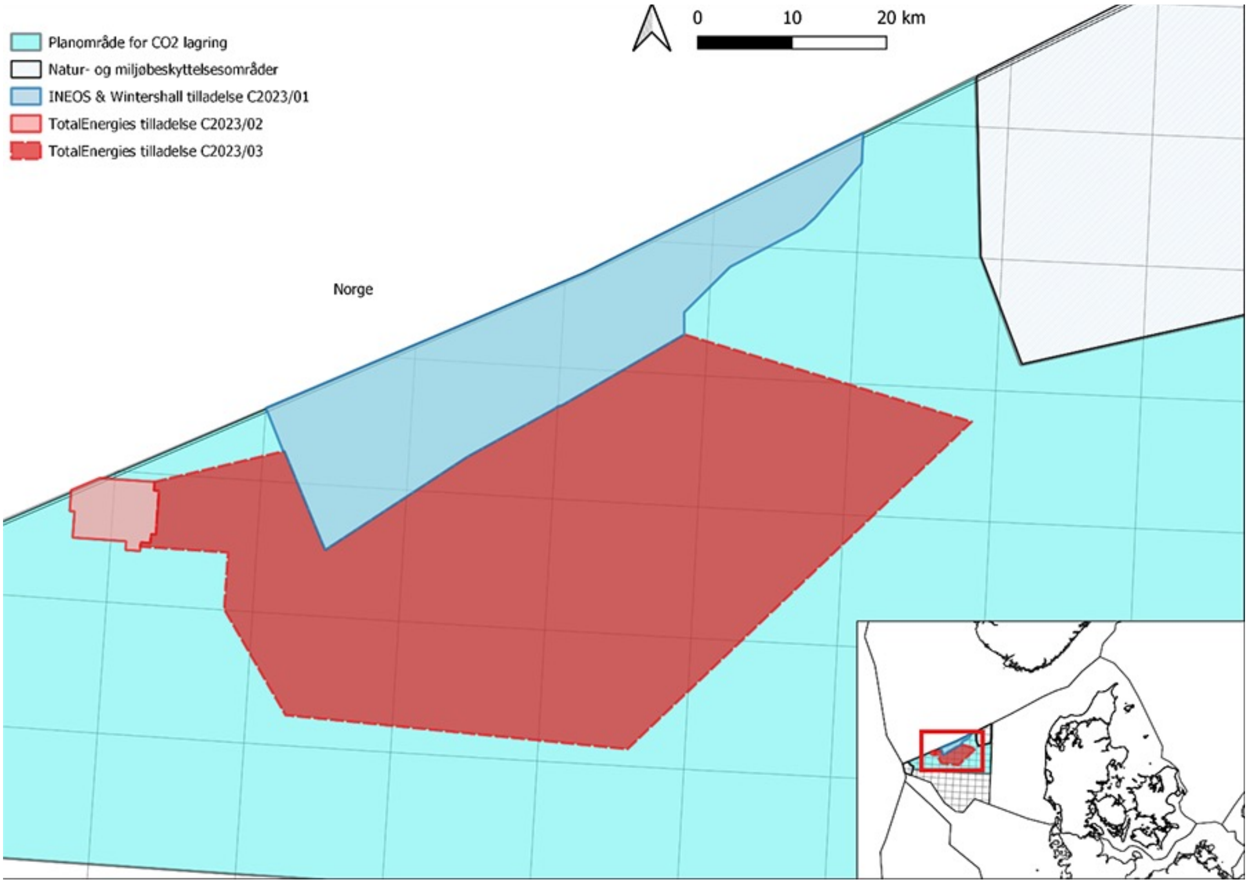
Once CO_2 is injected into these sandstone layers, it can be trapped in pore spaces, with the overlying claystone acting as a barrier to prevent any CO_2 leakage. Establishing storage facilities will necessitate adherence to stringent security measures, including comprehensive monitoring programmes to swiftly detect and address any potential CO_2 leaks effectively.[75]

Each option has its own maturation timeframe and advantages. Offshore storage in depleted oil and gas reservoirs builds on decades of technology development and data collection. Furthermore, infrastructure is in place, whereby the surface is connected to the subsurface. By taking advantage of the high initial SSRL, existing infrastructure and reservoir knowledge, this option provides a fast path to CO_2 storage in Denmark. At present, offshore storage in depleted chalk fields has a lower SSRL level than sandstone reservoirs, but as chalk is ubiquitous in the Danish underground, its storage potential should be further investigated. This type of reservoir could be developed based on our current knowledge of the reservoir. Offshore and onshore storage in saline aquifers in Skagerrak as well as nearshore and on land provides a large storage potential of several Gt CO_2. The location of CO_2 storage sites near-shore or on land can aid integration with power-to-x and other utilities and could thus provide the most optimal storage option in the long term.

Offshore storage

Denmark has awarded two offshore exploration licenses to a consortium of INEOS-Wintershall and to TotalEnergies.

Figure 18: Map of planning area for CO_2 storage, nature and environmental protection areas and permits C2023/01, C2023/02 and C2023/03



The INEOS-Wintershall consortium currently holds two exploration licences: The oil and gas fields situated in the Siri Canyon region (project Greensand) as well as an area of unexplored saline aquifers to the East. TotalEnergies holds two exploration licenses, one covering the existing oil and gas fields in the Harald area (Project Bifrost), and another unexplored area consisting of saline porous sandstone layers to the East.

75 Tilladelser til efterforskning og lagring af CO_2 og miljøhøringer | Energistyrelsen (ens.dk)

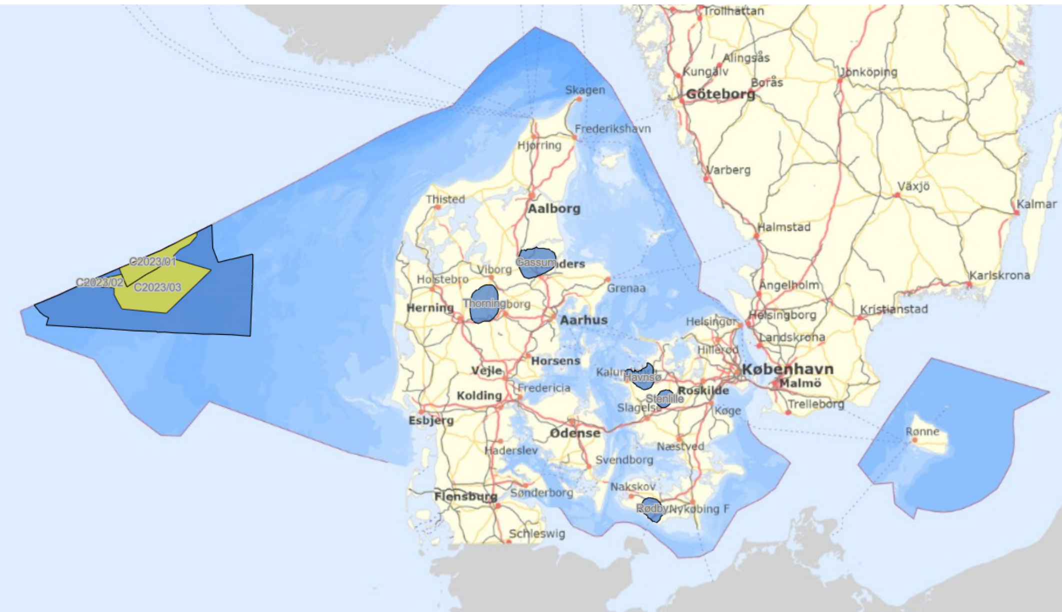
Storage projects

Greensand project: The primary aim of the Greensand project is to store between 0.5 and 1.5 Mt of CO_2 securely and permanently by 2025 and up to 8 million tonnes annually from 2030 in the INEOS-operated Siri area.[76] The project partnership has carried out a successful pilot for CO_2 storage in 2022 making Greensand the first operational large-scale CO_2 storage project in in Denmark. The captured CO_2 is coming from the INEOS oxide factory in Belgium. After liquefaction, it is transported via specialised containers to the Nini West platform in the North Sea via ship. At this location, the CO_2 is pumped into the underground through a dedicated well specifically designed for CO_2 injection. The CO_2 is being injected 1,800 meters beneath the seabed into a sandstone reservoir for permanent storage.

Bifrost project: Project Bifrost is aiming to establish a permanent offshore storage site for CO_2 owned by TotalEnergies, Noreco, Nordsøfonden (comprising offshore fields and associated facilities) and Ørsted (comprising pipelines). The objective is to sequester 3 million tonnes per annum of CO_2 around the Harald gas field, situated over 200 km from the Jutland coast. The Bifrost project also covers the development of an offshore floating unit serving as an intermediate storage and injection facility, facilitating the transport of CO_2 via ship. Furthermore, the project will repurpose existing gas pipelines for the transportation of CO_2 from shore. In addition to infrastructure development, Bifrost will advance monitoring technologies, protocols, and understanding of the socio-economic aspects associated with CCS deployment.[77]

Onshore storage

Figure 19: Danish CO_2 storage licensing map



Denmark is currently tendering exploration licences for geological storage of CO_2 within designated areas encompassing Gassum, Havnsø, Rødby, Stenlille and Thorning. Prior to the licencing round, a strategic environmental assessment has been conducted to ensure environmentally responsible storage practices.

76 SoG_WP_CarbonCapture_210x297_V09_Web.pdf
77 SoG_WP_CarbonCapture_210x297_V09_Web.pdf

The Danish Energy Agency has received 8 applications from 9 companies and is now evaluating the awarding of the exploration licences:

- → A consortium consisting of Equinor Low Carbon Solutions Denmark A/S and Ørsted Carbon Solutions A/S
- → A consortium consisting of Wintershall Dea International GmbH and INEOS E&P A/S
- → A consortium consisting of Wintershall Dea International GmbH and Equinor Low Carbon Solutions Denmark A/S
- → CarbonCuts A/S
- → Carbon Vault Denmark ApS
- → Capio Danmark Holding II ApS
- → Gas Storage Denmark A/S
- → Storegga Geotechnologies Limited[78]

CO_2RYLUS project: Gas Storage Denmark's CO_2RYLUS project aims to showcase the complete CCS value chain, from CO_2 capture to underground storage, while advancing industry knowledge. At Stenlille gas storage, natural gas is stored in porous sandstone more than 1,500 meters below ground, with a 300-meter claystone layer ensuring containment. This same structure is targeted for CO_2 storage. Leveraging over 30 years of operational experience and existing infrastructure, the project seeks to accelerate CCS in Denmark, emphasising onshore storage. It aims to permanently store up to 2Mtpa by 2029.[79] The reservoir at the existing gas storage site at Stenlille has properties like other potential storage sites in Denmark, and the results from field test pilots can be used to de-risk potential large scale onshore/near-shore storage sites. The subsurface is well known from more than 30 years of operations and thorough geological surveys. Gas Storage Denmark has great experience in public outreach and gaining acceptance for gas storage sites which they can share with future storage providers.

Innovation and R&D

Site specific investigation: There is a need for further site-specific investigations of the potential storage sites (particularly on land) to de-risk the storage complexes with respect to e.g., faults, compartmentalisation and to characterise the local injectivity and seal capacity.

Knowledge & information sharing: Research on geological formations takes a lot of time and resources. Seismic data for each reservoir must be acquired and there are several steps of drilling wells for data acquisition and test injections, which then have to be evaluated again. It is therefore important to ensure a proper knowledge and information sharing on underground data. Public data bases like the subsurface data base of GEUS are an important source of information.

Pressure & temperature impacts: A better understanding must be developed on how the difference in pressure levels and temperature before and after the CO_2 injection impacts the storage reservoir. This is especially relevant, when reservoirs are located close to each other to make sure that they do not interfere with each other. It is also important to investigate how temperature developments inside the reservoir impact the cap rock over different time periods. Different types of monitoring tools should be compared against each other and distinctions between onshore and offshore monitoring technologies must be further investigated.

Exploration methods: For the geological investigation of the Danish underground, so far seismic methods were applied to collect data on different geological structures onshore and offshore. It can be considered to explore and improve other methods of geophysical investigation like gravimetry or electromagnetic surveys. New technologies might be more cost or time efficient or might be applicable in areas, where seismic analysis is not feasible.

Interference with subsurface activities: Different geological formations for CO_2 storage are currently under research and evaluation. There is a need for studies on how storage sites interfere with other subsurface activities also with regards to evaluating and choosing future storage sites for CO_2.

Exploration of further reservoir storage sites: The currently awarded & tendered storage licenses do not represent the entire Danish storage capacity. A process for the investigation of further storage sites could be considered to foster the increase of larger volumes of CO_2 in the Danish underground for a faster realisation of Danish and international climate targets.

78 Ni selskaber vil lagre CO_2 i den danske undergrund | Energistyrelsen (ens.dk)
79 CO_2RYLUS - CO_2 lagring i Stenlille (energinet.dk)

Current SSRL for CO_2 storage solutions

Figure 20 shows the storage site readiness levels of the Danish onshore, nearshore and offshore storage sites. The onshore storage sites will move to SSRL 5 on award of a storage exploration licence in summer 2024. The storage sites have the potential to move more rapidly through SSRLs if some engineering work has been carried out prior to award and subject to permitting for appraisal work programme (including new seismic and wells). Licence C2023/03, although with exploration licence awarded, is still believed to be at a screening level of technical maturity.

For the storage sites currently in SSRL 4 a 3 -5-year period of evaluation is anticipated (assuming license award in June 2024) prior to injection in 2027/28 at the earliest. The tender process for the Danish nearshore licenses has not been announced yet but is expected to take place in the second half of 2024.

Figure 20: SSRL for CO_2 storage solutions

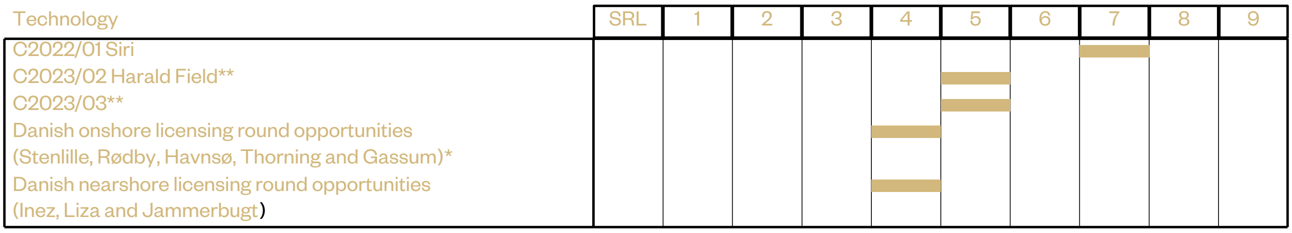


Figure 21 illustrates the announced CO_2 volumes and first years of injection for the presented storage projects.

Figure 21: Announced CO_2 volumes for Danish storage sites

Project	Storage year	CO_2 volumes per year
Greensand	2025 2027 2030	0.5 Mtpa 3 Mtpa 8 Mtpa
Bifrost	2030	5.5Mtpa
Stenlille	2026 2029	0.2 Mtpa 1-2 Mtpa

Conclusions

- → The announced joint storage capacities of at least 14.5Mtpa in 2030 are sufficient to store not only the 2.9 Mt covered by the Danish CCS funding schemes, but also the remaining ~1.5-3.5Mt shortcoming for reaching the 2030 target[80], if the missing reductions should be reached through CCS. This illustrates the demand for import of CO_2 to build a reliable long term business case for storage operators also beyond 2030.
- → There is a need for consolidating research and experience with monitoring technologies for CO_2 leakage and CO_2 plume migration into best practices for commercial and regulatory (safety) purposes.
- → There is a need to identify optimisation strategies in terms of cost and efficiency of different monitoring technologies.
- → There is a demand for optimised de-risking workflows of storage sites and storage capacities.
- → There is demand for low impact, fit for purpose data acquisition methods for subsurface de-risking.

80 Refer to chapter on CCUS reduction pathways

SRL maturity:

→ The listed storage projects Greensand, Bifrost and Stenlille are expected to reach SRL9 for large scale storage in 2030 the latest.
→ Greensand has announced large-scale injections from 2025.
→ Stenlille has announced to start first large-scale injections from 2026.

Determining factors for application

→ Sufficient CO_2 volumes for economically viable operation.
→ Sufficient geological and seismic data for de-risking of potential storage sites.
→ Experience with monitoring technologies for CO_2 leakage and CO_2 plume migration for safe operation.

CO_2 utilisation solutions

CO_2 utilisation solutions

Combining storage and utilisation of carbon with targeted impact

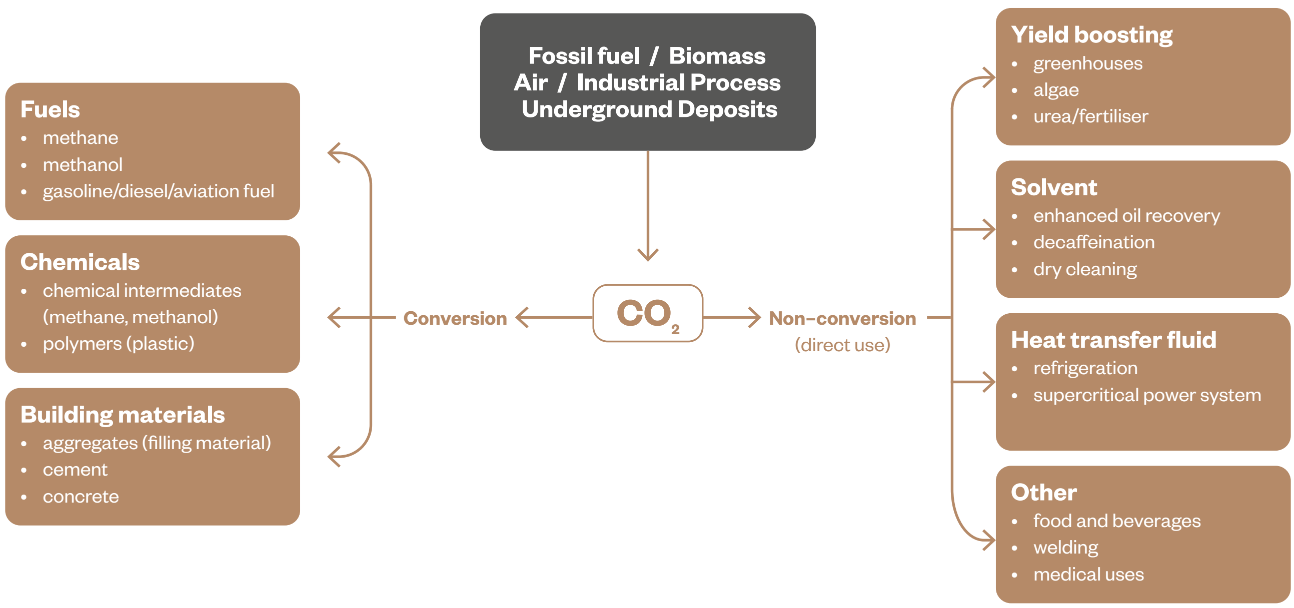
Transitioning from fossil-based carbon to atmospheric or biogenic carbon involves two key strategies: carbon capture and storage and carbon capture and utilisation. Addressing high fossil-based CO_2 emissions requires focused CCS efforts at major sources. Simultaneously, a strategy for building a cycle for atmospheric CO_2 as the primary source is essential since CO_2 is inevitable for certain chemical products and the production of sustainable building materials. Over time, fossil-based CCS will diminish in importance while CCS and CCU from atmospheric sources will grow. Balancing CO_2 storage and utilisation will evolve with technology and industry maturity.

CO_2 utilisation solutions

CO_2 utilisation technology encompasses the utilisation of CO_2 as a raw material for various products or services with potential market value. This approach spans two main avenues: Direct use, where CO_2 remains unchanged (non-conversion), and conversion, where CO_2 is transformed into a usable product.

Currently, around 7% of global fossil oil and gas is allocated for non-fuel purposes, a figure expected to remain relatively stable compared to the decline in fossil fuel use for energy[81]. Achieving carbon neutrality will require compensating remaining fossil CO_2 needed in chemical or building materials with atmospheric CO_2[82]. Biogenic carbon offers diverse applications, with the highest value attributed to human and animal nutrition, and the lowest to heat and electricity generation.[83] A market-driven approach can help balance biomass utilisation, conditional upon a proper assessment of CCU and CCS's climate impact.

Figure 22: Simple classification of pathways for CO_2 use



81 https://innovationsfonden.dk/sites/default/files/2021-08/Appendix%201%20_%201112-00010A%20-%20The%20Green%20CCUS%20Roadmap%20-%20Towards%20a%20fossil%20free%20future.pdf
82 "Construction Materials from CO_2 and Solid Waste" CSIRO
83 "Putting CO_2 to Use", National Academy of Sciences, 2019

Ongoing Danish research efforts based on biological processes for CO_2 utilisation involve direct synthesis of relevant products, and pathways over a variety of platform molecules. In addition, CO_2 can be utilised in production of gas grid-grade biomethane in highly efficient bioreactors, conversion to solvents, valuable commodity products such as carbocyclic acid, food ingredients, proteins, solvents, detergents and polymers. Further, biological processes allow for carbon conversion using hydrogen from renewable hydrocarbons, water electrolysis or biogas. Biological processes are capable of co-producing methane and CO_2, which can be integrated for further chemical production.

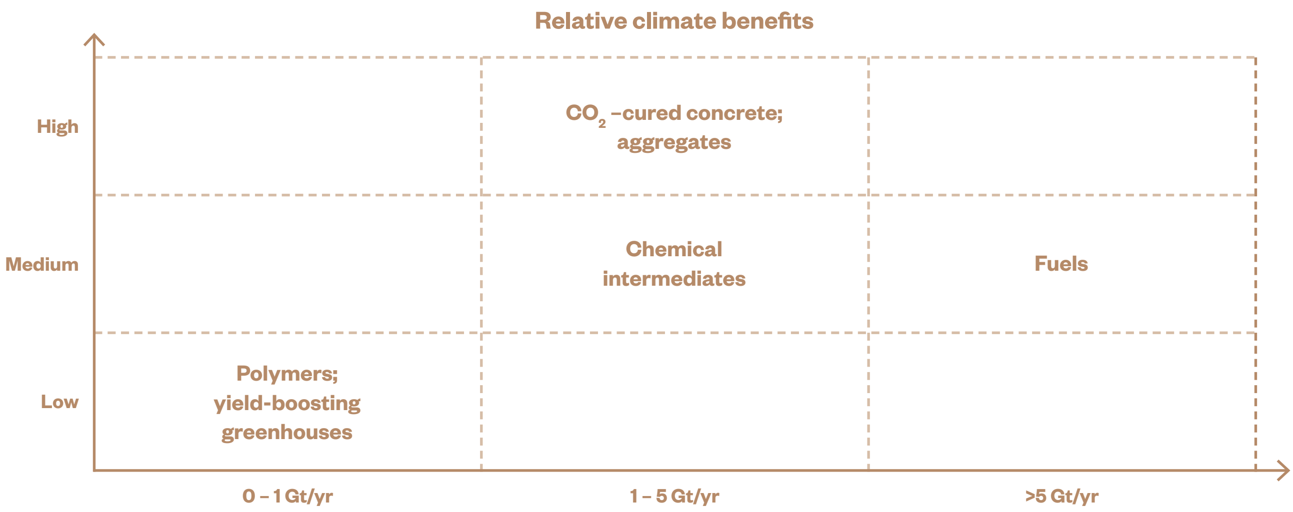
Through the EUDP, Denmark has facilitated several successful CO_2 utilisation demonstration projects and private funds have been allocated to development of e.g., CO_2-redusing catalysts. In order to ensure the transition from scientific publications into public companies, strategic funding for high TRL-projects is required.

The utilisation of CO_2 has the caveat that it does not necessarily reduce emissions. The potential climate reductions of CO_2 utilisation must be qualified by life cycle approaches for different CO_2 containing products. There are different factors that can inform the assessment of reduction potentials for utilised CO_2:

→ The CO_2 source
→ The original product that the biogenic CO_2-based product is replacing
→ The form of energy that is used for the conversion of CO_2
→ The timespan in which the new product is capturing CO_2
→ The upscaling potential for the CO_2 utilisation[84]

An assessment of the climate effects vs. theoretical potential for utilisation of CO_2 illustrates that building materials show the bigger positive climate effect, while fuels have the biggest market potential as illustrated in figure 23. The reduction potentials for CO_2 utilisation in chemicals and materials are expected to be relatively small compared to utilisation in fuels (due to marked size) and from CCS. CO_2 utilisation in materials can therefore complement CCS but is no alternative.[85]

Figure 23: Climate effect and market potential

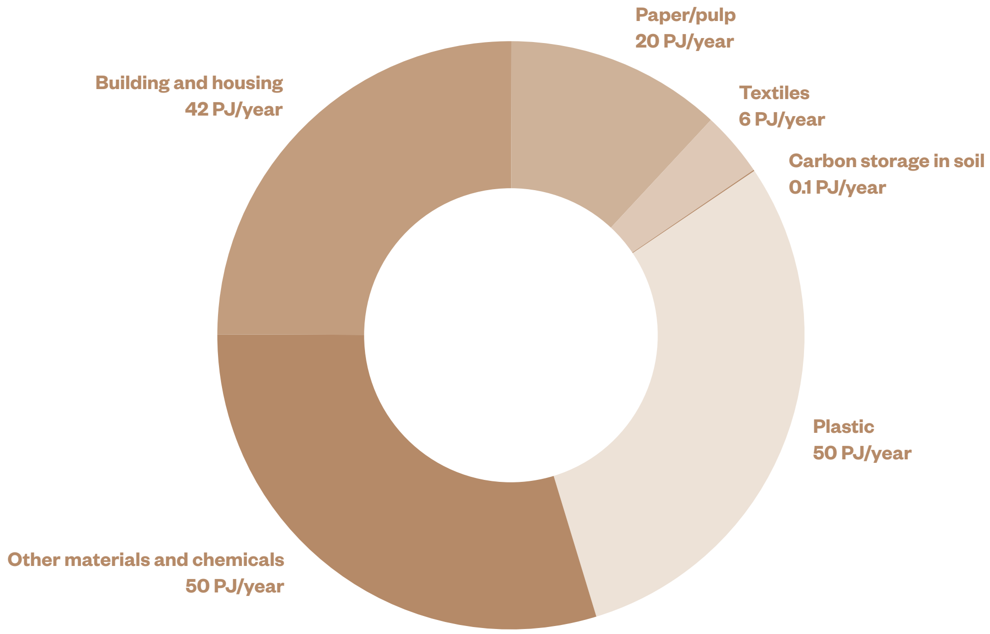


84 Putting CO_2 to Use – Analysis - IEA
85 Putting CO_2 to Use – Analysis - IEA

Biomass demand

On of the determining factors for the utilisation of CO_2 is the availability of sufficient biomass to get biogenic CO_2. Biomass is a scarce resource with its production being limited by environmental conditions, biodiversity and area planning. Figure 24 illustrates that there is a high expected demand for biomass especially for production of plastics, chemical and building materials jointly making up 168PJ which corresponds to ~8.9 million tons of dry matter. In 2019, ca. 2 million tons of dry matter were used in Denmark with the largest share consisting of straw (~1.5 million tons). It is estimated that the production can be increased to 12-14 million tons by increasing straw, grass, wood biomass and livestock manure volumes. It however also has to be considered larger land use for forest and nature areas, which would reduce the potential dry matter volumes to around ~10 million tons.[86]

Figure 24: Future demand of biomass for raw materials and materials



86 Det Biogene Kulstof_web.pdf (foodbiocluster.dk)

Innovation and R&D

CO_2 to biological algae cultivation and enzymatic conversion: This method uses algae and enzymes to convert CO_2 into biomass and other valuable products. It involves cultivating algae in large ponds or photobioreactors, focusing on optimising growth conditions and genetic modifications to maximise CO_2 fixation and overall efficiency.

→ **Challenges in algae cultivation:** Algae cultivation for CO_2 sequestration requires large areas for ponds, with high operational costs related to controlling growth and managing the drying process. Algae sensitivity to impurities and pH variations presents additional challenges.
→ **Enzymes & genetic modification:** There is significant research potential in identifying novel enzymes and pathways for more efficient enzymatic CO_2 conversion. Innovations could include optimising algae cultivation techniques within specialised photobioreactors and exploring genetic modifications to improve CO_2 fixation and product yield.
→ **Cost-effectiveness:** Developing cost-effective methods for large-scale implementation is crucial. This includes reducing the overall expense of cultivation setups and improving the efficiency of the algae growth and CO_2 absorption processes[87].

CO_2 to mineral carbonation and construction materials: Mineral carbonation represents a promising option for long-term carbon storage, producing industrial materials like calcium carbonate ($CaCO_3$) and magnesium carbonate ($MgCO_3$), used in construction, pharmaceuticals and coatings[88].

→ **Energy consumption:** Mineral carbonation involves high energy consumption and slow process kinetics, requiring substantial reagent amounts. There is also a potential for environmental pollution during the process.
→ **Process optimisation:** Efforts to enhance the carbonation process include incorporating waste materials and optimising parameters like gas pressure and reaction time. Innovative approaches, such as integrating carbonation with amine regeneration processes or using ultrasound, show promise in enhancing efficiency.
→ **Market and applications:** The application of carbonated minerals in industries like construction and pharmaceuticals is expanding. With a market projected to grow significantly, technologies like Carbfix are establishing the use of carbonation in various applications, emphasising the economic feasibility and environmental benefits of this approach89.

CO_2 to chemicals and durable materials: This approach transforms CO_2 into long-lasting chemicals and materials like urea and polycarbonate polyols. These processes are energy-intensive and require advanced technology for CO_2 purification and conversion, aiming to reduce carbon emissions by integrating CO_2 into useful products.

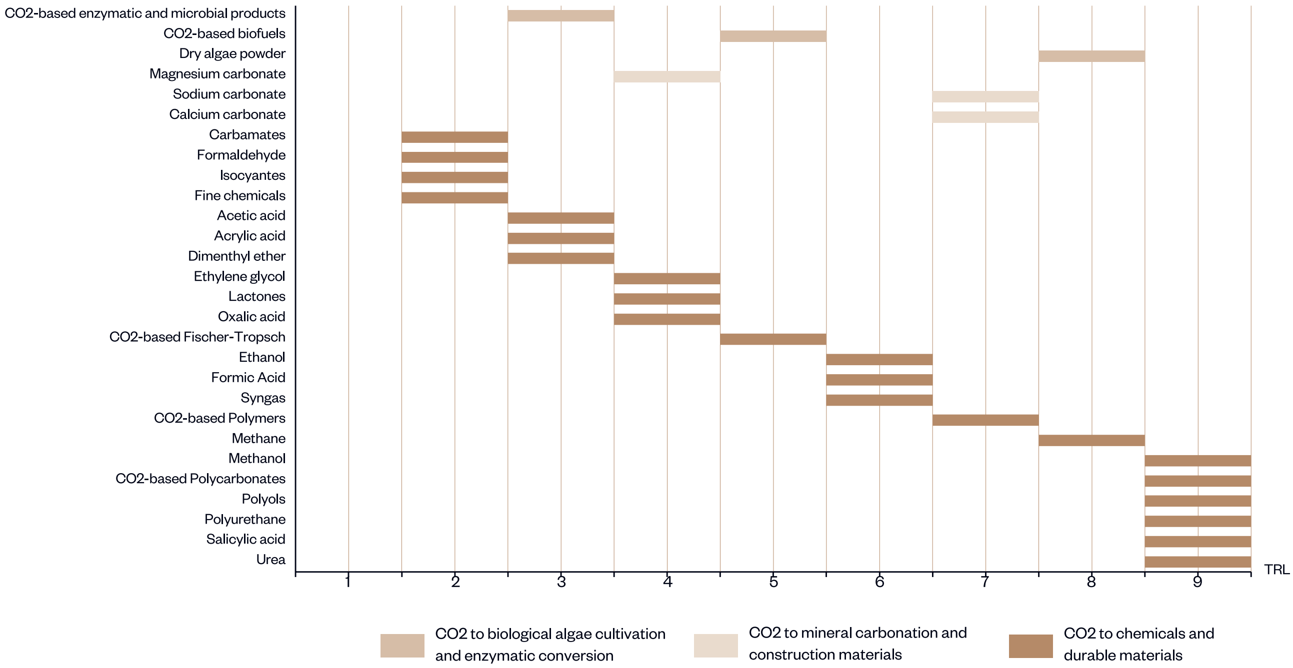
→ **Challenges in conversion processes:** The conversion of CO_2 into chemicals and durable materials faces high costs related to hydrogen and CO_2 purification, the need for advanced catalyst development and concerns over CO_2 leakage. These processes are also energy-intensive, requiring significant renewable energy inputs.
→ **Commercial viability:** Currently, only a few technologies, such as the production of urea and polycarbonate polyols, are commercially viable. Urea, although used as a fertiliser, can release carbon if not sourced from renewable energy, while polymers offer a more durable option for carbon utilisation in construction and electronics.
→ **Advancements needed:** Further technological advancements and market development are essential for the widespread adoption of these CO_2 conversion technologies. This includes enhancing the efficiency of processes and developing new applications for CO_2-derived products, such as methanol-to-x solutions90.

87 Review on the recent structural advances in open and closed systems for carbon capture through algae https://www.sciencedirect.com/science/article/pii/S2772427121000322
88 Review of carbon dioxide utilization technologies and their potential for industrial application - ScienceDirect
89 Review of carbon dioxide utilization technologies and their potential for industrial application - ScienceDirect
90 Review of carbon dioxide utilization technologies and their potential for industrial application - ScienceDirect

Current TRL for CO_2 Utilisation solutions

Figure 25 provides an overview of TRLs for CO_2 utilisation solutions in the categories biological algae cultivation and enzymatic conversion, mineral carbonation and construction materials and chemicals and durable materials.

Figure 25: TRL for CO_2 Utilisation solutions



TRL forecasted for CO_2 utilisation solutions

Figure 26 provides a forecast on the estimated time period needed by the presented CO_2 utilisation solutions to reach TRL 9 assuming a regular TRL development with continuous research efforts for each technology.

Figure 26: TRL forecast for CO_2 utilisation solutions

Technology	Status 2024	2030	2035	2040	2045	2050
CO_2 to biological algae cultivation and enzymatic conversion						
CO_2-based enzymatic and microbial products	3			9		
CO_2-based biofuels	5		9			
Dry algae powder	8	9				
CO_2 to mineral carbonation and construction materials						
Magnesium carbonate	4		9			
Sodium carbonate	7	9				
Calcium carbonate	7	9				
CO_2 to chemicals and durable materials						

Technology	Status 2024	2030	2035	2040	2045	2050
Carbamates	2				9	
Firmaldehyde	2				9	
Isocyantes	2				9	
Fine chemicals	2				9	
Acetic acid	3			9		
Acrylic acid	3			9		
Dimenthyl ether	3			9		
Ethylene glyc	4		9			
Lactones	4		9			
Oxalic acid	4		9			
CO_2-based Fischer-Tropsch	5		9			
Ethanol	6	9				
Formic Acid	6	9				
Syngas	6	9				
CO_2-based Polymers	7	9				
Methane	8	9				
Methanol	9					
CO_2-based Polycarbonates	9					
Polyols	9					
Polyurethane	9					
Salicylic acid	9					
Urea	9					

Conclusions

- → Utilisation of biogenic CO_2 in chemicals and materials is an essential tool to establish an atmospheric carbon cycle.
- → The biggest variety in solutions can be found in chemicals and durable materials.
- → There is a lack of knowledge on reduction potentials of the different CO_2 utilisation solutions.
- → There is a lack of knowledge on Danish market strongholds for CO_2 utilisation in chemicals and materials, which would be an important parameter to incentivise targeted innovation and development of these solutions.
- → The utilisation of CO_2 in chemical and materials is mostly relevant for emission reductions in a 2050 perspective. Considering the low TRL of several solutions within the field, this still requires ongoing research today to ensure that an atmospheric CO_2 cycle can be established until 2050.
- → It must be assessed in which categories of CO_2 utilisation Denmark has the biggest reduction and market potentials. (Comparable to the assessment of main Danish emitters for improving capture from point sources.)
- → There is need for a more detailed assessment of products and materials, where the replacement with biogenic CO_2 is environmentally and economically best suited vs. where it is more economically viable to geologically store CO_2.
- → There is the need for life cycle analysis of products that can be produced with biogenic CO_2 to assess the holistic reduction potentials of CO_2 utilisation solutions.
- → Further analysis is needed on how to establish an atmospheric CO_2 cycle and which societal and industrial transitions are needed to ensure a completed transition by 2050.

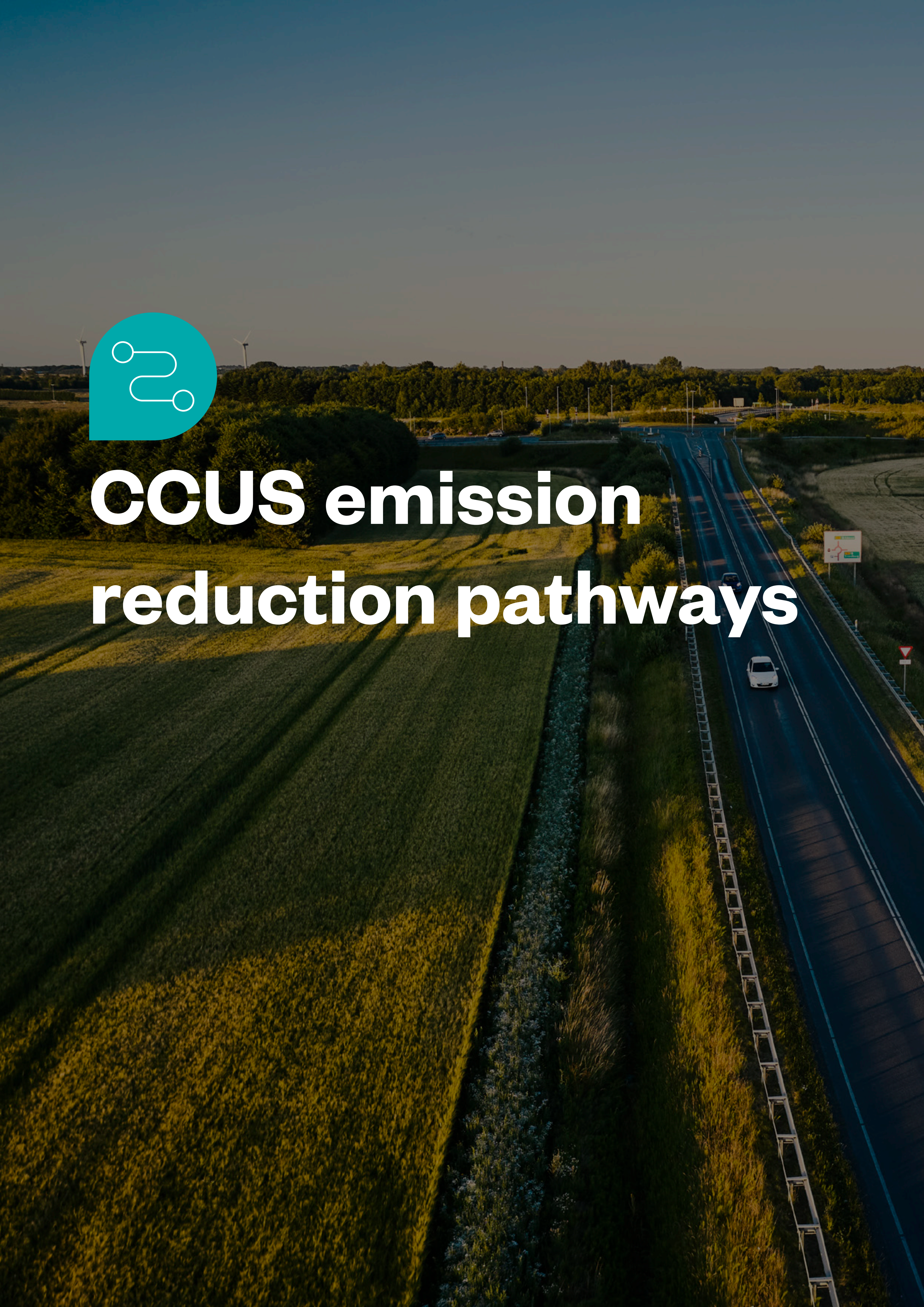
TRL maturity

- → The TRL overview shows that 50% of the described CO_2 utilisation solutions are comparably immature with a TRL blow 6.
- → There is a large variety of solutions that have the potential to be matured to TRL 9 in 2030. This would require continuous and even research and innovation focus on several solutions.
- → To ensure the establishment of an atmospheric CO_2 cycle in 2050, a larger variety of CO_2 utilisation technologies needs to be matured to TRL 9.

Determining factors for application

- → Availability of sufficient biomass
- → Competition of utilisation vs. storage costs for CO_2

CCUS emission reduction pathways



CCUS emission reduction pathways

This chapter presents an analysis of different CCUS reduction pathways. The following emission inventories and 2030/2050 scenarios are being applied:

→ The Danish climate status & outlook 2024.
→ The Danish Energy Agency's analyses of technical capture potentials from point sources and other CCUS solutions.
→ The Danish Energy Agency's 2030 & 2050 scenarios for climate neutrality (KP22 scenarios).
→ The EU impact assessment report on reaching climate neutrality in 2050.
→ The IEA Net Zero scenario for 2050.

The Danish climate status & outlook 2024

The Danish climate status & outlook 2024 (KF24) is considering CCS emission reductions covered by the public CCS funding schemes which combined are supposed to deliver 2.9Mt CO_2 reduction in 2030. Figure 27 illustrates the amount of Danish emissions in 2022 with agreed reductions from CCS (2.9Mt) and other climate actions (~11.5Mt) in comparison to the targeted emission reduction down to 23.5Mt in 2030 for reaching the 70% target. The graph illustrates that there is a current shortcoming of ~1.5-3.5Mt to reach the 2030 target.

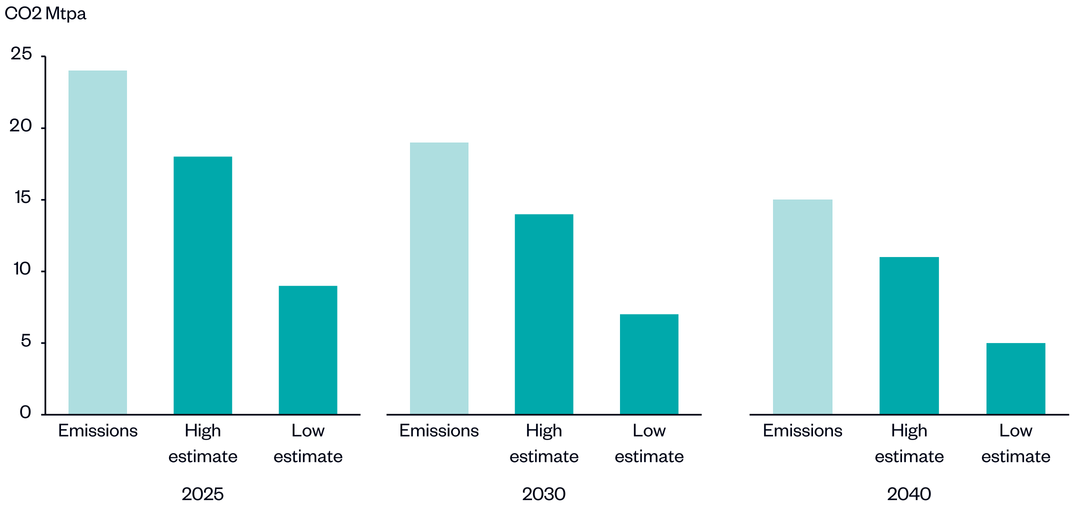
Figure 27: Status of target fulfilment in relation to the Danish climate act's 70% reduction target in 2030

In the following section, technical reduction potentials of different CCS solutions will be held against the climate target for 2030 to assess how much additional reduction potential can be achieved by applying higher volumes and additional CCS solutions.

Reduction potentials for CO_2 capture from point sources

The Danish Energy Agency estimates the technical capture potential from point sources to be between ~7 – 14 Mtpa in 2030. For the following reduction scenarios, an average of ~10.5 Mtpa in 2030 will be applied.

Figure 28: Total CO_2 emissions and capture potentials from point sources



There are four main groups of CO_2 point sources in Denmark:

- → Industry production: An estimated range of 1.8 to 3.6 million tons of CO_2 emissions per year.
- → Electricity and district heating production: Approximately 1.6 to 3.2 million tons of CO_2 emissions annually.
- → Waste incineration: An estimated range of 1.3 to 2.7 million tons of CO_2 emissions annually.
- → Biogas upgrade: Approximately 0.7 to 1.3 million tons of CO_2 emissions per year.

A large share of the CO_2 captured in Denmark will come from the industry and power generation sector. The third biggest sector is represented by waste incineration plants. This is relevant to consider for further development of capture technologies focusing on capture from heavy industry like cement and combined heat and power plants. The composition of the flue gas is dependent on the emitter and affects the capture potential of different technologies. To redeem the displayed capture potential from point sources, future research would also need to focus on capture technologies with the possibility of retrofitting existing plants.

Figure 29: Estimated capture potential from point sources divided by sectors

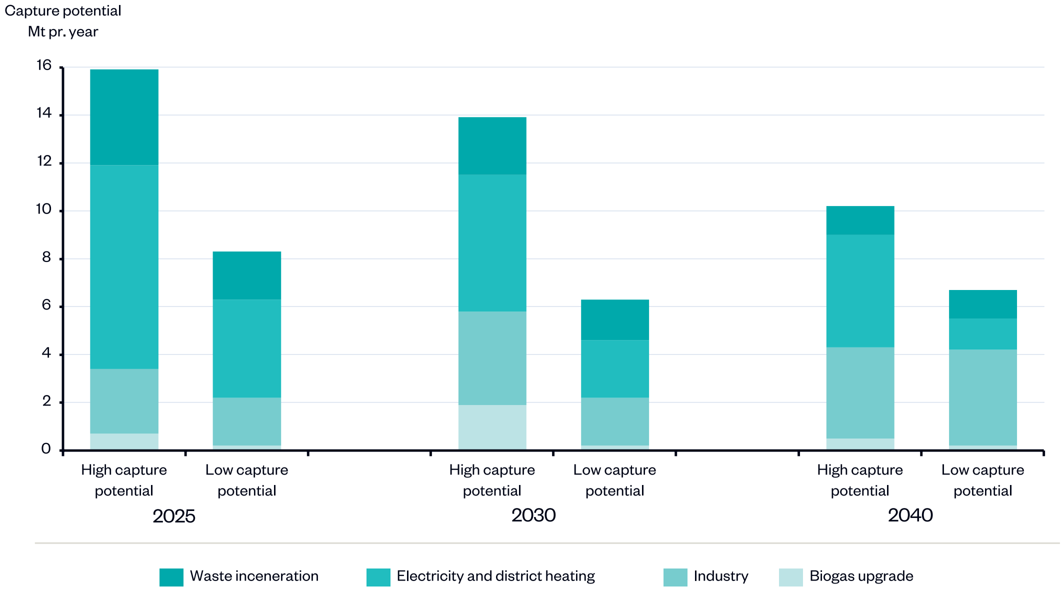


Figure 29 illustrates the capture potential divided by fossil, biogenic and process emissions. An average of ~3 Mtpa is anticipated to come from fossil fuels, process emissions in industry, and the fossil component of combustible waste in 2030. A large share of the captured CO_2 (~7 Mtpa) is projected to be derived from biogenic sources in 2030 (figure 30). For developing an atmospheric carbon cycle, it is important that a sufficient share of the biogenic CO_2 is made available for the utilisation in green carbon products or permanent storage for negative emissions. This illustrates the importance of fostering technologies supporting efficient CO_2 capture from biogenic sources. It also underlines the necessity to further develop a robust carbon market for biogenic CO_2 certificates.

Figure 30: Estimated capture potential from point sources divided by form of CO_2

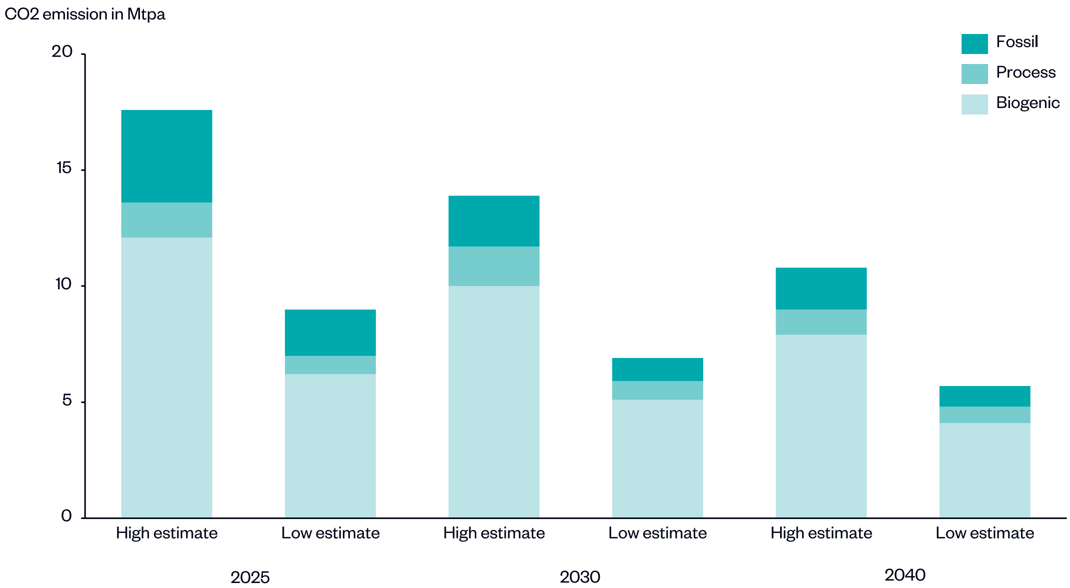


Figure 31: Capture from point sources & DAC

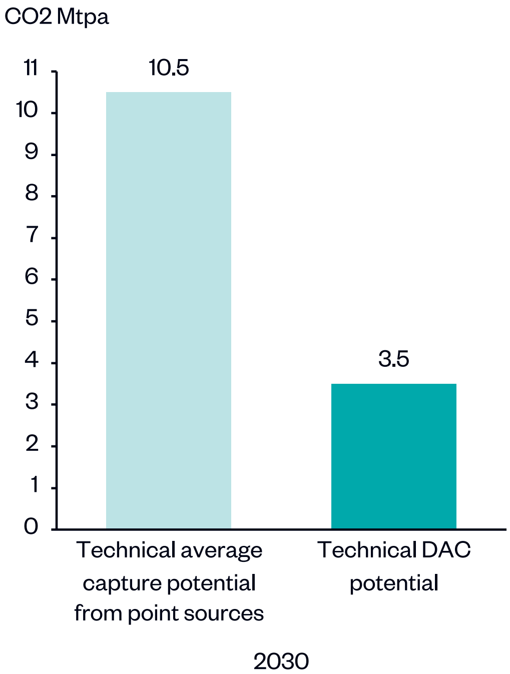


Figure 32: Capture from nature-based solutions & PtX fuels

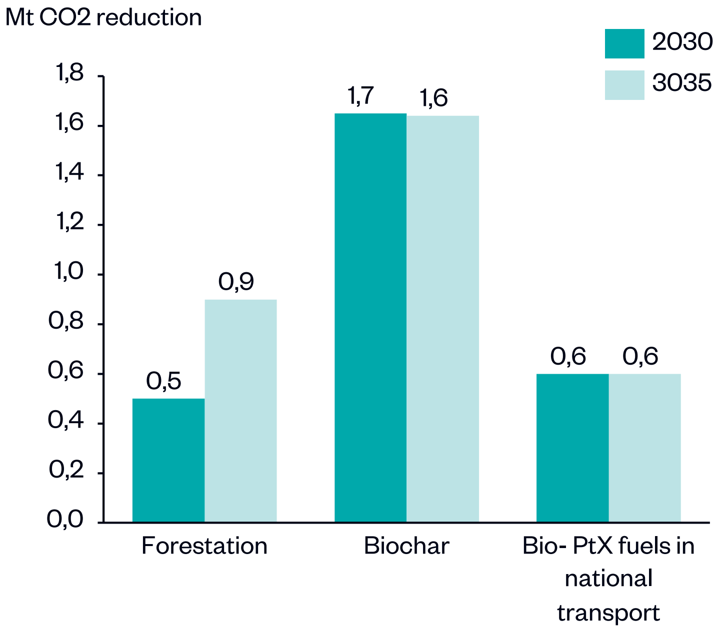


Figure 31 illustrates Denmark's estimated average technical potential for CO_2 capture from point sources compared to the technical potential for DAC in 2030. The comparison shows that the highest reduction potentials lie in capture from point sources with ~10.5 Mtpa compared to DAC with 3.5 Mtpa assuming the availability of 1GW wind energy. Figure 32 illustrates the technical capture potential for NbSs and in comparison, the technical reduction potentials from bio and power-to-x fuels in 2030 and 2035. From the displayed solutions, biochar has the highest capture potential in 2030 with 1.7 Mtpa. In general, it can be observed that there is a low data availability on capture potentials from NbSs. More research is needed to evaluate capture potentials from the other NbSs of soil sequestration, wet- and peatland restoration and enhanced rock weathering introduced in the solution mapping chapter. Additionally, further research into reduction potentials from CO_2 utilisation in other materials and processes than green fuels is needed to be able to provide a holistic assessment of different reduction pathways and reduction potentials from all available CCUS technologies.

In the beginning of this chapter, it was illustrated that Denmark is currently calculating with 2.9 Mtpa of emission reductions from CO_2 point source capture in 2030. Moreover, it was illustrated that there is a shortcoming of ~1.5-3.5Mt emissions to reach the 70% target of 23.5 Mt in 2030. In figures 33 and 34, the combination of the technical reduction potential of chosen CCS solutions is assessed in scenarios to illustrate, which CCS technologies can further contribute to closing the current emission reduction gap and to potentially reach further emission reduction than the 70% target by 2030. The Danish government has in its political programme introduced the target of climate neutrality by 2045, which would increase the need for additional reduction beyond the 70% target in 2030.

Figure 33: Scenarios 1-7 for additional technical reduction potentials to close the 2030 emissions shortcoming

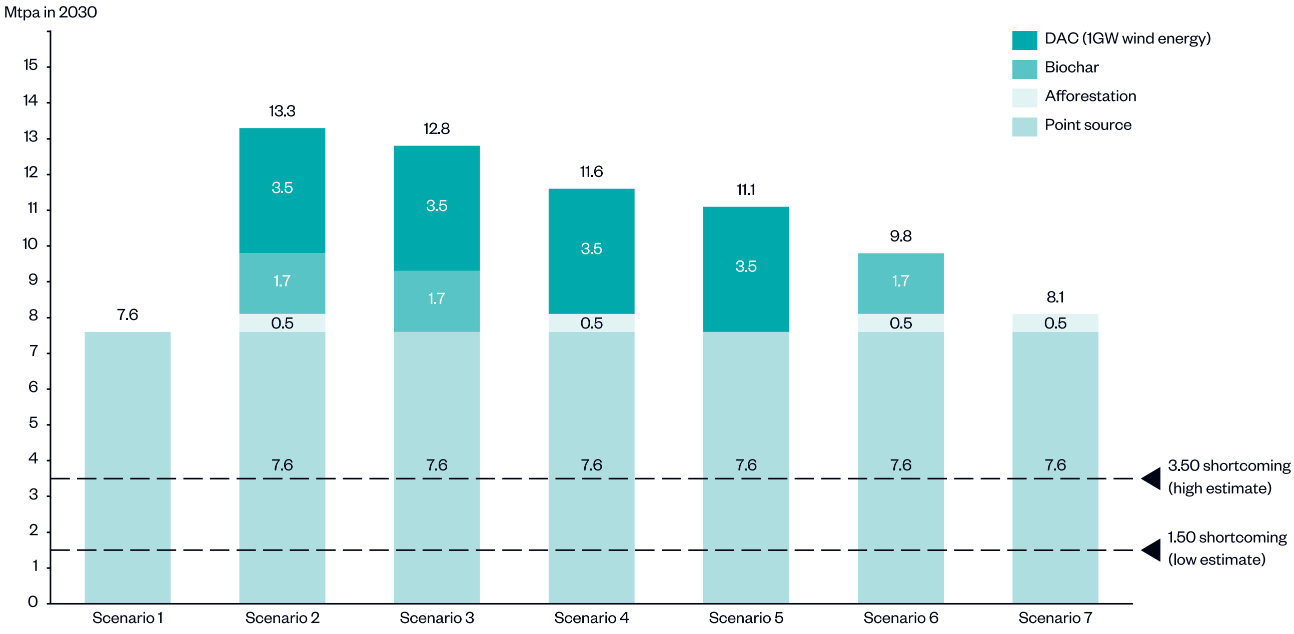
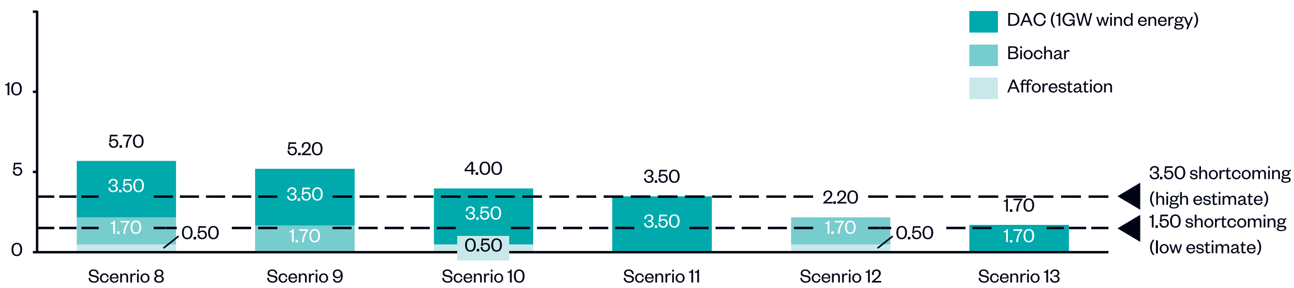


Figure 34: Scenarios 8-13 for additional technical reduction potentials to close the 2030 emissions shortcoming



**In the scenarios, 2.9Mt from point source capture are deducted from the total point source capture potential of ~10.5Mt since they are already considered in the calculation of the Danish climate status & outlook KF24.The graph applies average numbers from the referenced reports[91][92]*

Scenario 1 in figure 33 illustrates that capture from point sources yields an additional reduction potential of ~7.6Mtpa in 2030, which would exceed Denmark's current emission gap of ~1.5-3.5Mt and reach additional reductions of~ 4.1-6,1Mtpa. Exploiting the total technical potential of carbon capture from point sources would reduce overall emissions to up to ~19.4Mt in 2030. Solution pathway 2 illustrates the maximum technical reduction potential of ~13.3Mt combining point source capture, DAC and nature-based solutions. This would reduce the overall emissions to up to ~13.7Mt in 2030. Another option is to extent capture from point sources by the short coming of ~1.5-3.5.4Mt and to apply DAC and NbSs as buffer capacity.

Figure 34 shows scenarios combining DAC and NbSs. By applying the maximum technical capacity of all three displayed solutions, a reduction potential of 5.7Mt can be reached, which exceeds the current reduction shortcoming for 2030. Already only the application of the full technical DAC potential would reaching the high estimate of the reduction gap of 3.5Mt. Only the application of biochar with a technical potential of ~1.7Mt[93] would close the lower estimated gap of ~1.5Mt in 2030.[94]

91 Microsoft Word - KP22_TRP_notat_131222_renset.docx
92 Microsoft Word - Punktkilder til CO_2 - potentialer for CCS og CCU 2022-opdatering.docx (ens.dk)

94 The scenarios do not cover the total variety of nature-based solutions that are available. Further solutions like enhanced rock weathering of soil carbon sequestration can potentially deliver further emission reductions, which could not be considered in the scenarios due to a lack of data at national level. The same applies to reduction potentials from CO_2 utilisation in other applications than green fuels, which can yield further reductions not being considered in the illustrated pathways due to a lack of data at a national level.

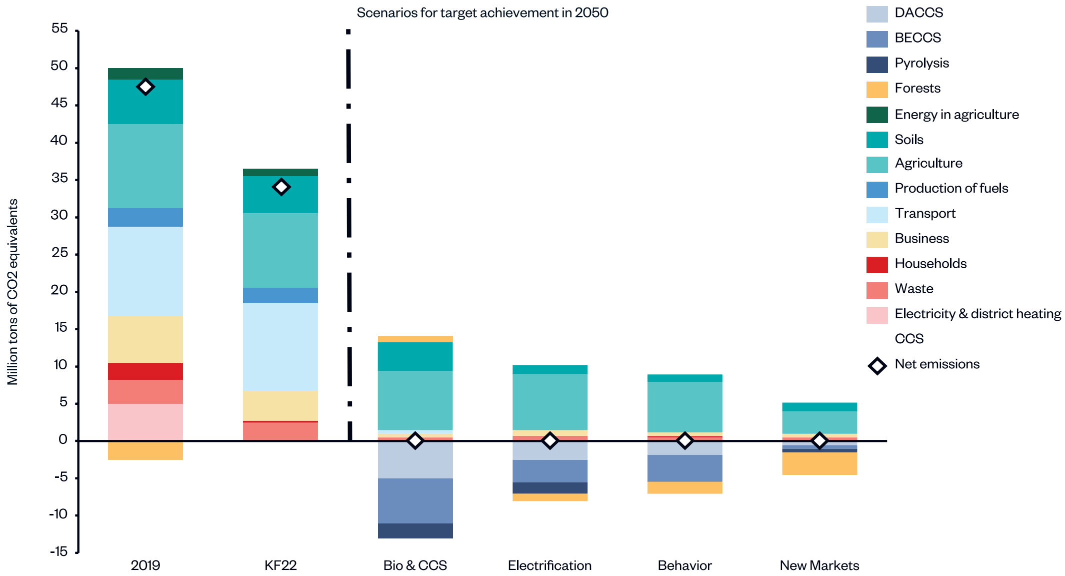
When looking at the presented solutions pathways, it must be considered that it is difficult to realise the technical potential of all presented solutions within real world constraints like e.g., availability of sufficient renewable energy, space for technology application or sufficient market incentives for the respective solutions. In the following paragraph different scenarios for reaching the 2030 and 2050 target will be discussed to illustrate dependencies and preconditions for the large-scale application of CCUS solutions.

DEA 2030 & 2050 scenarios

The 2050 scenarios by the DEA assume notable variations, particularly regarding the level of emissions remaining in agriculture, land use and forests by 2050. This influences the extent of compensation required through negative emissions.

The scenarios assume that CO_2 emissions arising from waste and the process emissions from cement production in the industry will comprise a blend of biogenic and fossil CO_2. Within this mix, a portion of CO_2 is utilised in fuel production scenarios for CCU. Consequently, this entails minimal fossil emissions from CCU, which are subsequently balanced out by negative emissions. These emissions are accounted for in CO_2 equivalent (CO_2e) figures, with BECCS serving as a mechanism to offset them. Fossil CCU amounts to 0.0-1.0 Mt of CO_2e in the 2050 scenarios.[95]

Figure 35: DEA scenarios for 2050



- In the Bio & CCS scenario a significant number of negative emissions is derived from BECCS, DACCS and pyrolysis with ca. ~13 million tons CO_2e in 2050.
- In the electrification scenario, the total requirement for negative emission technologies is ~8 million tons of CO_2e, significantly less than in the Bio & CCS scenario. Furthermore, the application of BECCS is notably reduced. At the same time, there will be a rise in afforestation leading up to 2050 in accordance with the forest plan.
- The reduction in livestock numbers in the behavioral scenario reduces the demand for feed. This makes it possible to ded icate more areas for increased afforestation (approximately 60 percent of the area). This leads to a higher net CO_2 absorption from forests, totaling 1.6 million tons of CO_2e. The behavioral scenario requires fewer negative emission technologies such as pyrolysis, BECCS, and DACCS compared to the electricity scenario.
- The new market scenario is assuming most reductions from a radical green transition of the agricultural sector. In return there is less need for negative emissions and the largest share is covered by afforestation. BECCS, DACCS and pyrolysis play a limited role.

The overall outlook for 2050 indicates that the application of CCS technologies is dependent on the emissions from agriculture and land use. With higher emissions from agriculture and land use, there is a bigger demand for negative emissions from BECCS, DACCS and pyrolysis. Afforestation effort expand with lower emission reductions from agriculture and land use.

To put the 2050 scenarios in perspective, figure 36 illustrates the 2030 assumptions that the 2050 scenarios are built upon.

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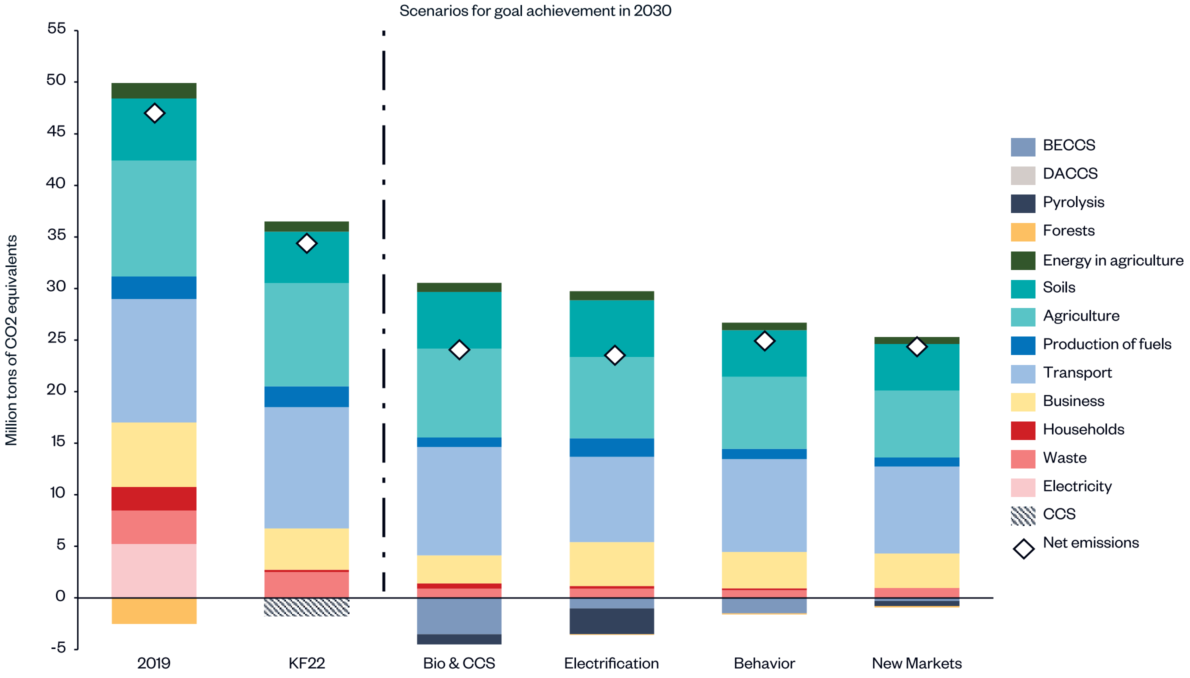
Figure 36: DEA scenarios for 2030



With a perspective on CCUS solutions in the Bio & CCS, it is important to note that:

1. BECCS is assumed to already contribute to negative emissions with a share of ~3.5Mt CO_2e.
2. Pyrolysis is assumed to contribute to negative emissions with ~1Mt CO_2e.
3. Emission reductions from DACCS and afforestation are not considered for the delivery of negative reduction in the 2030 scenario.

Figure 37 illustrates a comparison of the DEA 2030 & 2050 scenarios with the technical reduction potentials for the presented CCS solutions.

Figure 37: Comparison of DEA 2030 & 2050 scenarios with technical reduction potentials[96]

	Average technical reduction potential in 2030	**DEA 2030 Bio & CCS scenario**	**DEA 2050 Bio & CCS scenario**
BECCS	Biogenic: ~7Mtpa	BECCS: ~3,5Mtpa negative emissions	~6Mtpa negative emissions
DAC(CS)	DAC: ~3.5Mtpa	DACCS: 0 Mtpa negative emissions	DACCS: ~5 Mtpa negative emissions
Pyrolysis (biochar)	Biochar: ~1.7Mtpa	Pyrolysis: ~1 Mtpa negative emissions	Pyrolysis: ~2 Mtpa negative emissions
Afforestation	~0.5Mtpa	0Mtpa negative emissions	0Mtpa negative emissions
	Average technical potential in 2030	**DEA 2030 electrification scenario**	**DEA 2050 electrification scenario**
BECCS	Biogenic: ~7Mtpa	BECCS: ~1Mt negative emissions	BECCS: ~3Mtpa negative emissions
DAC(CS)	DAC: ~3.5Mtpa	DACCS: 0Mtpa negative emissions	DACCS: ~2.5Mtpa negative emissions
Pyrolysis (biochar)	Biochar: ~1.7Mtpa	Pyrolysis: ~2.5Mtpa negative emissions	Pyrolysis: ~1.5Mtpa negative emissions
Afforestation	~0.5Mtpa	~0.1Mtpa negative emissions	~1Mtpa negative emissions
	Average technical potential in 2030	**DEA 2030 behavioral scenario**	**DEA 2050 behavioral scenario**
BECCS	Biogenic: ~7Mtpa	BECCS: ~1.5Mtpa negative emissions	BECCS: ~3.5Mtpa negative emissions
DAC(CS)	DAC ~3.5Mtpa	DACCS: 0Mtpa negative emissions	DACCS: ~1.8Mtpa negative emissions
Pyrolysis (biochar)	Biochar: ~1.7Mtpa	Pyrolysis: 0Mtpa negative emissions	Pyrolysis: ~0.1Mtpa negative emissions

96 The numbers can vary slightly from the original values as they are read off directly from the graph in the report and not from the original dataset.

Afforestation	~0.5Mtpa	~0.1Mtpa negative emissions	~1.6Mtpa negative emissions
	Average technical potential in 2030	**DEA 2030 new markets scenario**	**DEA 2050 new markets scenario**
BECCS	Biogenic: ~7Mtpa	BECCS: ~0.3Mtpa negative emissions	BECCS: ~0.5Mtpa negative emissions
DAC(CS)	DAC: ~3.5Mtpa	DACCS: 0Mtpa negative emissions	DACSS: ~0.5Mtpa negative emissions
Pyrolysis (biochar)	Biochar: ~1.7Mtpa	Pyrolysis: ~0.5Mtpa negative emissions	Pyrolysis: ~0.5Mtpa negative emissions
Afforestation	~0.5Mtpa	~0.1Mtpa negative emissions	~3Mtpa negative emissions

BECCS

In all scenarios, BECCS is applied to reach negative emissions already from 2030. In scenarios with enhanced focus on CCS, BECCS is supposed to deliver ~1-3.5Mtpa in 2030 and ~3-6Mtpa in 2050. This underlines the role of research in point sources capture technologies in a 2030 and 2050 perspective. The DEA estimates a technical capture potential for biogenic CO_2 of ~7Mtpa in 2030. This means that there is assumed to be enough available capture potential for biogenic CO_2 to reach the assumed negative emission sin 2030 and 205. However, this requires that capture technology from point sources is mature enough and scalable to reach the assumed volumes. There is a small variety of technologies for capture from point source - especially amine solvents in post-combustion technologies - with TRL 7-9, which are forecasted to be matured to TRL 9 in 2030. The TRL forecast shows that there are additional point source capture solutions with a TRL 6-7 which have potential to be matured to a TRL 9 in a 2030 perspective presuming continuous research efforts. The capture potential from point sources is highly influenced by the respective emitters and composition of their flue or syngas. To reach bigger volumes in 2050, a bigger variety and more efficient solutions tailored to emitters will be needed to ensure the delivery of sufficient negative emissions for the scenarios with strong focus on BECCS application. Considering a 2040-2050 perspective, research should also focus on improving pre-combustion, oxyfuel combustion or chemical looping combustion capture solutions as they yield a higher efficiency potential due to higher CO_2 concentrations in the gas in earlier stages of production.

It must be considered that the DEA forecast for technical point source capture currently expects a decrease in volumes for capture of biogenic CO_2 from ~7Mt in 2030 to ~4.75Mt in 2040. Sufficient negative emissions from BECCS in 2050 could be reached through an increased share of biogenic CO_2 in remaining plants or the building of additional bioenergy plants. For the building of new plants, the retrofitting suitability of the capture technology would be less relevant, which makes pre-, oxyfuel and looping combustion more attractive in a 2040 and 2050 perspective. However, the building of new plants would require the availability of sufficient biomass production. It is therefore important to steer the technology development with a holistic perspective taking into account required technologies in a post 2030 perspective, while balancing needs for immediate emission reductions to reach the climate targets in a pre-2030 perspective. Moreover, realising the capture potential is highly dependent on the TRLs along the entire CCS and CCU value chain.

DACCS

DAC is assumed to have a technical reduction potential of 3.5Mt in 2030. The current estimated TRL for DAC is 6 with a forecast for maturing DAC to TRL 9 for large scale application in 2030 presuming continuous research efforts. The DEA 2030 scenario does not consider negative emissions from DACCS. If DACCS was to deliver earlier emission reductions up to 2030, this would require significant research focus and investments in the technology, which in return would reduce investment possibilities in other CCUS solutions. In the 2050 scenario, DACCS is assumed to play an important role in delivering negative emissions having the second largest share of negative emission with ~2.5-5Mtpa in scenarios with strong focus on CCS application. It is therefore important to keep a continuously strong focus on the development and effectivisation of DACCS throughout the coming decades to be able to reach 2050 capacities. This will also require the availability of sufficient volumes of renewable energy.

Biochar

Biochar is assumed to have a technical reduction potential of 1.7Mt in 2030. Pyrolysis is assumed to deliver reductions in all scenarios from 2030 (excluding the behavioural scenario) with ~1-2.5Mtpa in 2030 and ~1.5-2Mtpa in 2050. In the electrification scenario, it is assumed to deliver up to 3Mt negative emission in 2030, which exceeds the currently expected technical reduction potential of biochar in 2030. (It has to be considered that pyrolysis also covers bio-oil and biocoke production.) Biochar is assumed to have a TRL of 6-7 today. Following the TRL projections, the technology is ready for large scale application around 2030. Reductions in large volumes from biochar in 2030 would therefore require a bigger research focus and investment to push the technology to TRL 9 before 2030 to reach volumes of ~1-2.5Mt negative emissions. The assumed volumes of emission reduction in scenarios with high biochar application do also require sufficient biomass for production and land for application.

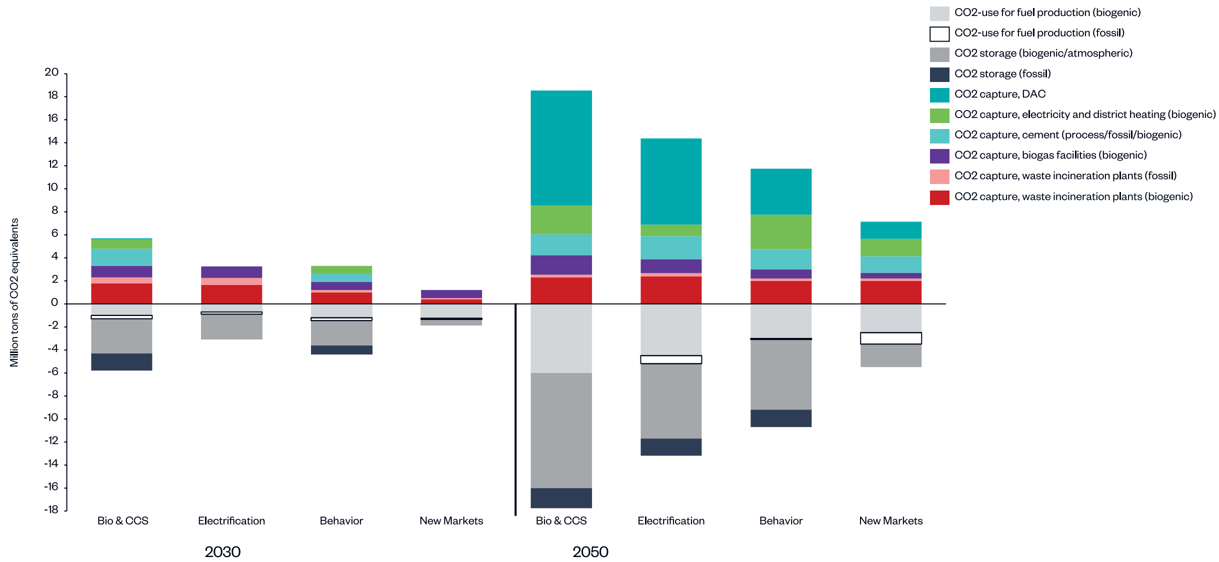
Afforestation

Afforestation is assumed to have a technical potential of delivering 0.5Mt emission reduction in 2030. However, none of the scenarios are calculating with reductions from NbSs in 2030. When looking at the 2050 scenario, high amounts of negative emissions from afforestation are assumed, when comparing it to the technical potential in 2030. The new marked scenario has the highest assumption with 3Mtpa. This scenario would require utilisation of substantial areas of land for realisation. The higher the assumed remaining emissions from land use and agriculture, the lower the role of afforestation will be in the presented scenarios.

Since it is uncertain, if agriculture and land use will reach sufficient emission reductions for scenarios with high CCS application or high afforestation, it necessary to put similar research and innovation efforts in both areas to ensure the availability of both solution pathways up to 2050.

In the chapter on solution mapping for CO_2 capture from point sources, it was concluded that it is important to develop capture solutions targeted to emitter types that will still be present in 2050. Figure 38 presents an overview of capture volumes from prevalent emitter types in 2030 and 2050.[97]

Figure 38: DEA scenarios for CO_2 capture in 2030 & 2050



In contrast to figure 35 & figure 36, figure 38 illustrates the total capture, storage and utilisation activities for capture from point sources and DAC required to reach the 2030 and 2050 target. This means that not only the share of negative emissions, but also the capture, utilisation and storage of remaining fossil emissions is considered. Moreover, figure 38 shows that a large share of captured CO_2 is assumed to contribute to fuel production. Fossil CO_2 is to a certain extent also used for fuel production depending on the scenario. It is important to note that figure 38 does not specify contributions by NbSs applied in figures 35 & 36.

By 2030, CO_2 captured from point sources includes emissions from biogas, waste, industry (e.g. commercial cement), and electricity production (biomass-fired plants), with variations based on scenario. Again, it becomes apparent that there is a high reliance in all scenarios on the capture and storage of biogenic CO_2 through BECCS. By 2050, due to increased demand for CO_2 in fuel production and negative emissions, capture from point sources is not sufficient anymore. A significant amount of CO_2 is consequently captured from the atmosphere through DAC.

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Figure 39: Comparison of DEA 2030 & 2050 capture scenarios with technical reduction potentials

	Average technical potential in 2030	DEA 2030 Bio & CCS scenario	DEA 2050 Bio & CCS scenario
CO_2 capture from point sources (incl. biogenic CO_2)	~10.5Mtpa	~5.5Mtpa	~8Mtpa
DAC	~3.5Mtpa	~0.1Mtpa	~10Mtpa
	Average technical potential in 2030	**DEA 2030 electrification scenario**	**DEA 2050 electrification scenario**
CO_2 capture from point sources (incl. biogenic CO_2)	~10.5Mtpa	~3Mtpa	~6.5Mtpa
DAC	~3.5Mtpa	0Mtpa	~7.5Mt
	Average technical potential in 2030	**DEA 2030 behavioral scenario**	**DEA 2050 behavioral scenario**
CO_2 capture from point sources (incl. biogenic CO_2)	~10.5Mtpa	~4Mtpa	~7Mtpa
DAC	~3.5Mtpa	0Mtpa	~4Mtpa
	Average technical potential in 2030	**DEA 2030 new markets scenario**	**DEA 2050 new markets scenario**
CO_2 capture from point sources (incl. biogenic CO_2)	~10.5Mtpa	~2Mtpa	~4.5Mtpa
DAC	~3.5Mtpa	0Mtpa	~1.5Mtpa

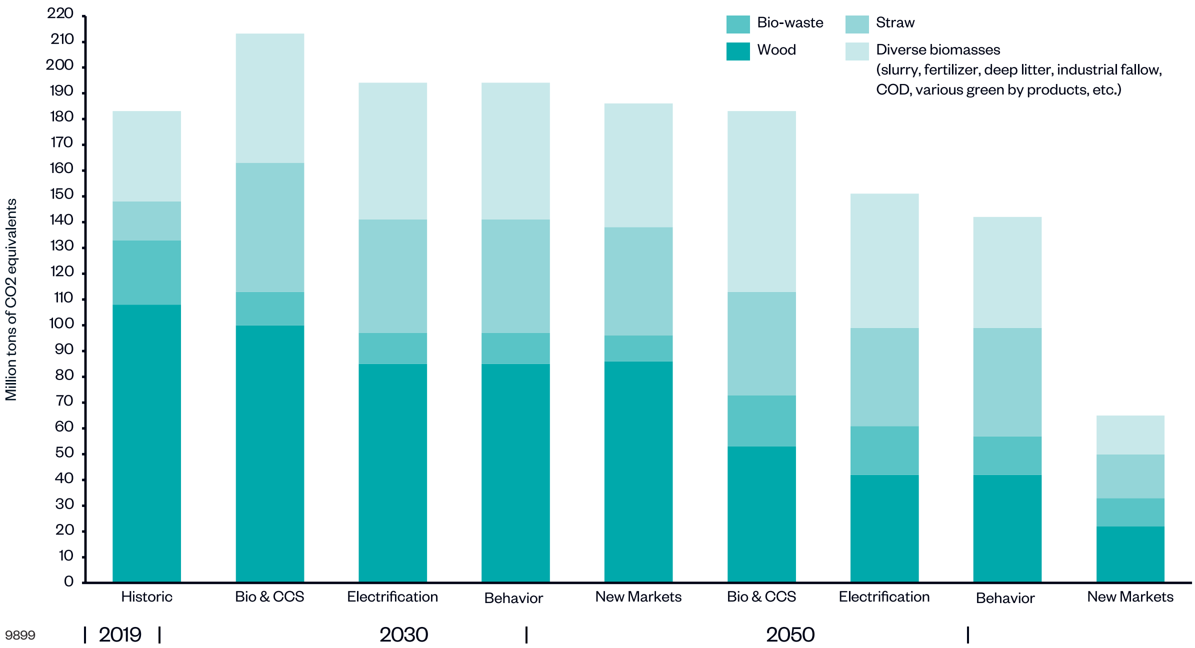
CCS (incl. biogenic CO_2)
In all scenarios, CCS is applied for emission reductions ranging from ~2-5.5Mtpa in 2030 and ~4.5-8Mtpa in 2050. None of the scenarios are reaching the technical potential of ~10.5Mtpa in 2030. However, three of the presented scenarios exceed the 2.9Mtpa of point source capture agreed in the Danish CCS funding schemes. To reach bigger volumes in 2030 & 2050, a bigger variety and more efficient solutions tailored to specific emitter types prevalent in Denmark is needed to ensure the delivery of sufficient emission reductions for the scenarios with strong focus on CCS application.

DAC
DAC is assumed to have a technical reduction potential of 3.5Mt in 2030 (assuming availability of 1GW wind energy). The Bio & CCS scenario considers DAC in small volumes of ~0.1Mtpa in 2030. The other scenarios do not consider DAC in 2030. The current estimated TRL for DAC is 6, which is assumed make DAC ready for large scale application in 2030. If DAC is supposed to deliver the 0.1Mtpa in 2030 from the Bio & CCS scenario or even higher volumes up to the technical potential of 3.5Mtpa, this would require significant research focus and investments in the technology to ensure a faster maturing to TRL 9 before 2030. In the 2050 scenario, DAC is assumed to play an important role in delivering emission reductions with a span of ~1.5Mtpa - 10Mtpa depending on the scenario. It is therefore important to keep a continuously strong focus on the development and effectivisation of DAC throughout the coming decades to be able to reach 2050 capacities. This will also require the availability of sufficient volumes of renewable energy. Figure 38 illustrates that depending on the scenario, a share of up to ~50% of the captured CO_2 from DAC is foreseen to be utilised (DACCU). It has to be considered that DAC and CO_2 utilisation currently are among the CCUS solutions with the highest energy penalty. Applying high volumes of DACCU will require enhanced research into improving energy efficiency for both solutions.

Projected biomass demand for the DEA scenarios
In the chapter on solution mapping for BECCS and NbSs, it was outlined that the application of these solutions will require large amounts of biomass, which has to be provided under sustainable conditions considering environmental and biodiversity boundaries. The 2030 & 2050 scenarios are based on the below consumption of biomass.

Figure 40 illustrates the biomass consumption for energy in different scenarios. None of the scenarios project biomass consumption exceeding the 2019 historic level of around 190 PJ by 2050. In fact, three scenarios indicate a notable decrease in consumption due to differences in the assumed biomass allocation for energy purposes.

Figure 40: Consumption of biomass for energy purposes in the scenarios compared with the historical consumption in 2019.



[98][99]

Figure 41: Overview of biomass consumption

	2019	2050			
	Historical	**Bio & CCS**	**Electrification**	**Behaviour**	**New markets**
Total biomass consumption (PJ)	187	188	150	136	64
Biomass consumption per citizen (GJ/pers.)	33	31	25	23	11

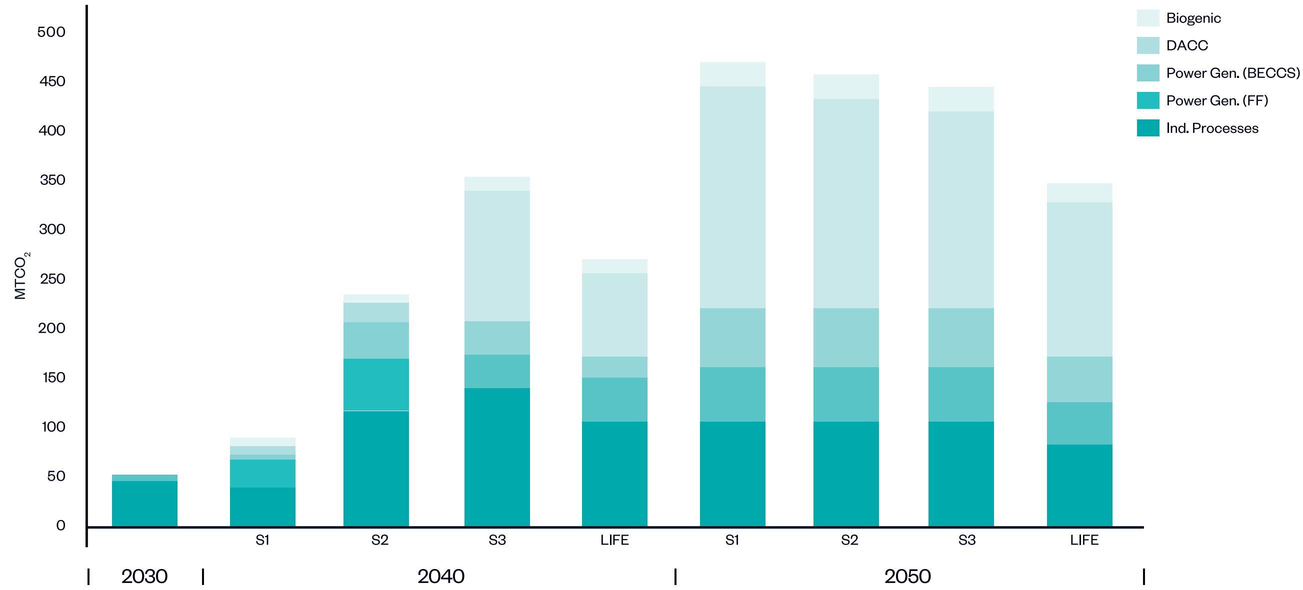
In all scenarios, wood consumption decreases compared to historical levels, especially by 2050. Additionally, bio-waste for electricity/heat production diminishes due to decreased waste production and higher recycling rates. The scenarios show an increase in the utilisation of straw and various other biogenic residual products from agriculture, forestry, and households. This increase in utilisation aims to support the intensified production of sustainable energy gas, primarily biogas.

EU impact assessment scenarios for net zero in 2050

For putting the Danish 2030 and 2050 scenarios into perspective, figure 42 illustrates the European PRIMES scenarios for 2030 and 2050.

98 Resultater for KP22-scenarier_clean_23-09-2022_Final_clean (ens.dk)
99 The numbers can vary slightly from the original values as they are read off directly from the graph in the report and not from the original dataset.

Figure 42: EU impact assessment scenarios for carbon capture by source

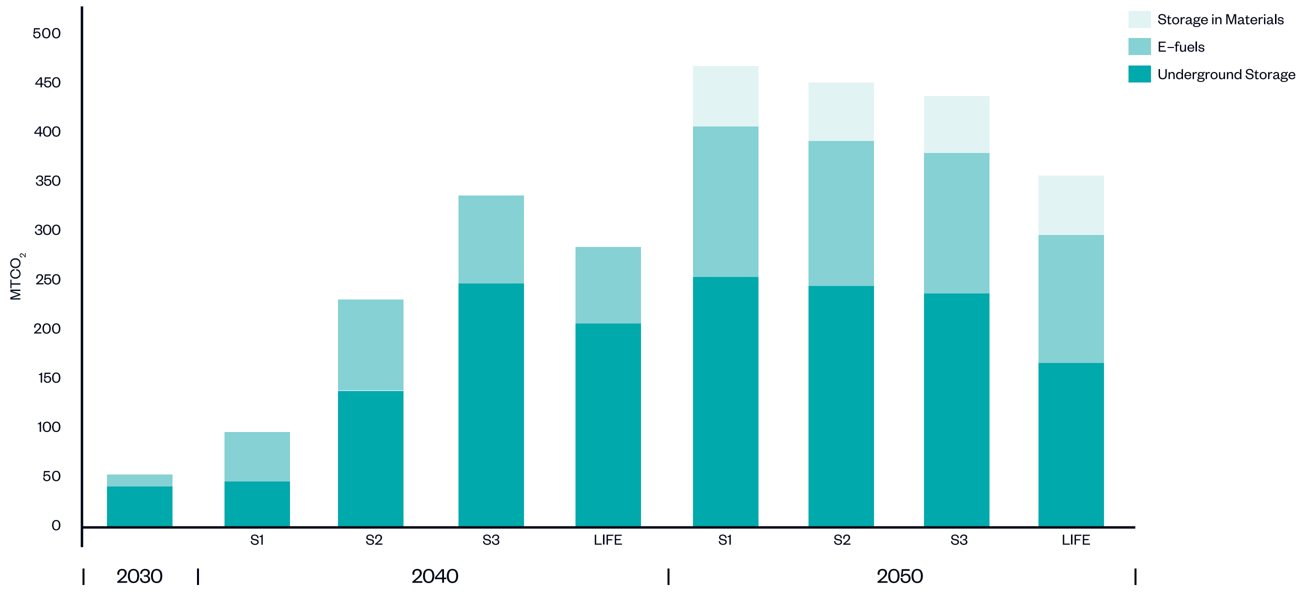


Note: Biogenic: This refers to carbon of biogenic origin, which typically involves CO_2 capture from bioenergy processes such as the combustion of biomass or from the upgrading of biogas to biomethane. Ind. Processes: Industrial processes involve capturing emissions from various industrial processes that contribute significantly to total greenhouse gas emission including several sectors such as refineries, chemical plants, iron and steel production, non-metallic minerals (such as cement and ceramics), and others. Power Gen. (BECCS): In Power Generation with Bioenergy with BECCS, CO_2 is captured from bioenergy combustion processes. Power Gen. (FF): This involves capturing CO_2 from power generation processes that burn fossil fuels. The captured CO_2 may then be stored or used, thus helping to reduce emissions from one of the traditionally high-emitting sectors. Source: PRIMES

In scenario S1, carbon capture focuses on industry and power generation, with minimal BECCS, biomethane upgrading, and DAC. In S2, a greater adoption of the technology initially results in increased levels of fossil carbon captured from industrial processes and power generation, followed by a utilisation of industrial removals, particularly BECCS. By 2040, DAC deployment rises due to biomass limits and e-fuel demand, more so in S3. By 2050, distribution of technologies is similar across scenarios. The LIFE scenario mirrors this trend with less DAC emphasis by 2040 and lower overall capture in 2050.

Figure 43 suggests that from 2030 to 2050 carbon capture not only reduces emissions in sectors that are difficult to address but also produces significant carbon feedstock for e-fuels or fossil-free products, along with industrial removals like BECCS and DACCS. This involves establishing an actual carbon management sector that connects different carbon technologies and sources to final end-user applications via industrial feedstocks, thus ensuring the harmonisation of carbon flows within the EU economy.

Figure 43: EU scenarios for carbon captured by end application



When comparing the EU scenarios to the scenarios by the DEA, it becomes apparent that there is a comparable split between CO_2 capture from point sources and application of DAC. The share of DAC in the Danish case is slightly higher than in the EU case. Moreover, Denmark is counting on a larger application of BECCS due to a higher share of biogenic materials in industrial and power generation processes.

IEA net zero scenario

Figure 44: IEA global reductions potentials for 2030 & 2050

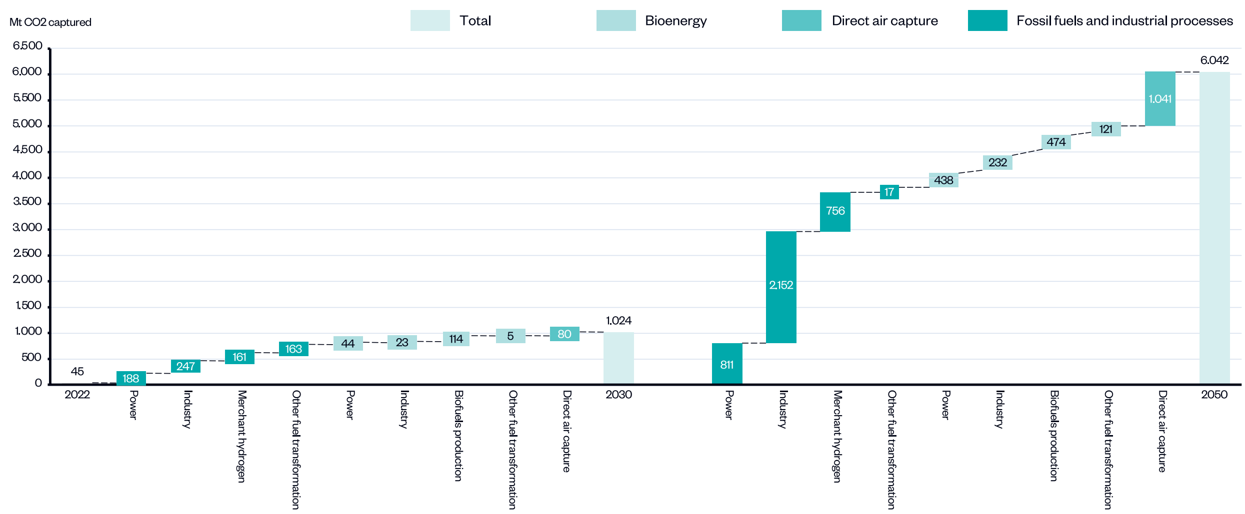


Figure 44 illustrates the global reduction potentials from CO_2 capture divided by sectors including DAC. Comparable to Denmark, the biggest capture potential at a global level is estimated to come from the industry and power sector. However, the share of biogenic CO_2 in these processes is much lower globally compared to Denmark. This underlines Denmark's important role in fostering technology development for the capture of biogenic CO_2, demonstrating the implementation of an atmospheric CO_2 cycle and supporting the development of business models for biogenic CO_2 e.g., through the strengthening of the voluntary carbon market and a strong focus on utilisation of biogenic CO_2.

Figure 45: Global reduction potential of NbSs in 2050

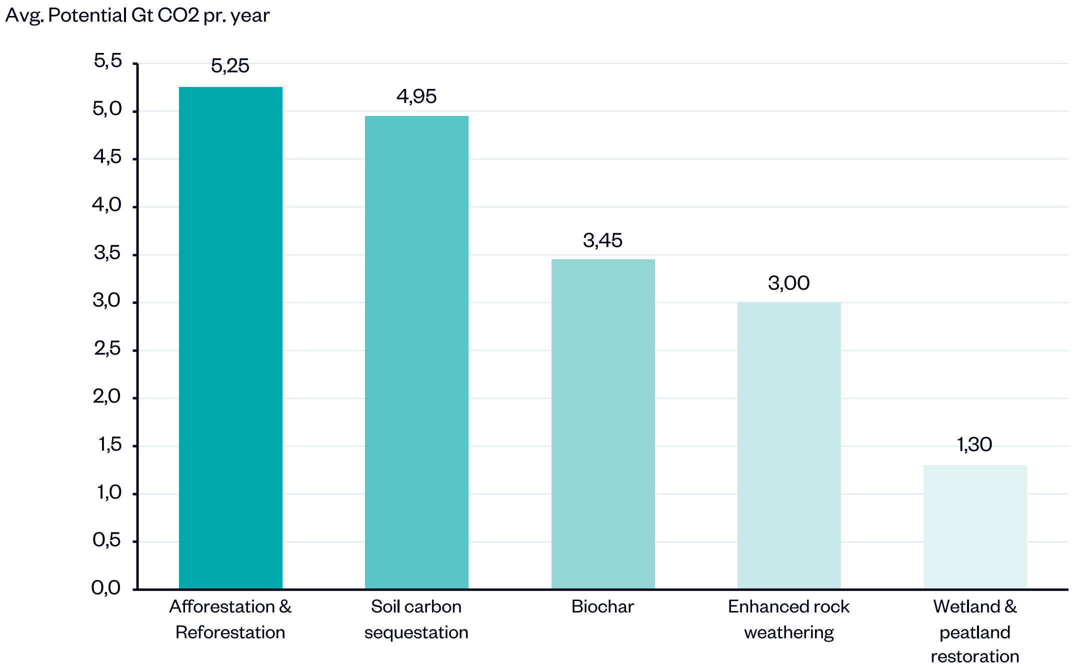


Figure 45 illustrates potentials of NbSs at a global level. The highest capture potential is attributed to afforestation and reforestation with 5.25Gt closely followed by 4.95Gt from soil carbon sequestration in 2050. Enhanced rock weathering shows a comparably high capture potential of 3Gt, which highlights the relevance of assessing the technologies reduction potentials in a Danish context. It must be stressed that especially the application of NbSs is highly dependent on the geography of application. It is therefore important to consider national perspectives for the application of these technologies.

Conclusions

→ **In the DEA 2030 and 2050 scenarios, the application of CCS technology for negative emissions is interlinked with the expected emissions from agriculture and land use. The application of CCS increases, if emissions from agriculture and land use are expected to stay high. Afforestation efforts expand with lower emission reductions from agriculture and land use.**

→ **The DEA scenarios have a strong focus on the delivery of negative emission from BECCS in 2030 and from BECCS and DACCS in 2050.**

→ **BECCS is assumed to deliver a large share of negative emissions ranging from ~1-3.5Mtpa in 2030 and ~3-6Mtpa in 2050 in scenarios with strong CCS focus.**

- The technical potential of point source capture from biogenic sources is estimated to be ~7Mtpa in 2030. This shows that sufficient amounts of biogenic CO_2 from point sources are estimated to be available for capture. However, the capture technology has to be mature enough for upscaling in order to deliver sufficient capture volumes.
- There is a variety of technologies for capture from point source especially within post-combustion solutions with TRL 7-9, which can be applied for emission reductions up to 2030.
- Technologies with TRL 9 still require development, optimisation and monitoring in long-term application. They moreover require development of supporting systems – e.g. for CO_2 purity and emission monitoring – around the core technology.
- Large scale implement will require continuous cooperation between industry and universities beyond TRL 9.
- A larger variety of solutions with higher efficiency for specific emitter types are required to reach the targeted negative emission volumes in 2050.
  - The prevalent emitter types in Denmark are industry production, electricity and district heating production, waste incineration and biogas upgrade.
- BECCS for negative emissions requires the utilisation of biogenic carbon which is a limited resource and dependent on utilisation of large amounts of lands, while establishing a production that is compatible with nature and biodiversity.
  - None of the scenarios project biomass consumption exceeding the 2019 historic level of around 190 PJ by 2050. Three scenarios indicate a notable decrease in consumption due to differences in the assumed biomass allocation for energy purposes.
- The presented EU scenarios assume a lower share of capture from biogenic sources and a higher share of capture from industrial processes. In a Danish context, the industrial emissions also cover biogenic CO_2.

→ **All scenarios apply significant amounts of CO_2 capture from point sources (biogenic & fossil) ranging from ~2-5.5Mtpa in 2030 and ~4.5-8Mtpa in 2050.**

- These levels do not exceed the technical capture potential from point sources of 10.5Mtpa in 2030.
- Scenarios with strong focus on CCS application do however exceed the agreed 2.9Mtpa from the Danish subsidy schemes in 2030.
- This underlines an even stronger demand for a larger variety of capture solutions from point sources and a development of tailored solutions for the identified emitter types in both a 2030 and 2050 perspective.

→ **The DEA scenarios show a strong distinction between DAC and DACCS.**

- In 2030, the Bio & CCS scenario is assuming a small share of DAC of ~0.1Mtpa. All other scenarios only consider DAC in 2050.
  - DAC is assumed to have a technical potential 3.5Mt in 2030 assuming the availability of 1GW wind energy for operation.
  - DAC has today an overall TRL of 6 and is expected to reach TRL 9 around 2030.
  - If the 0.1Mtpa or higher volumes up to the technical potential of 3.5Mtpa are to be reached in 2030, this would require significant research focus and investments to push the technology to TRL 9 at a faster pace.

→ **In 2050, the DEA scenarios are calculating with amounts of 1.5-10Mtpa emission reductions from DAC.**

- In scenarios with high focus on CCS, the volumes of carbon capture from DAC exceed the volumes of capture from point sources by up to ~2Mtpa in 2050.
- The increased DAC demand is partly driven by increased demand for CO_2 in fuel production and negative emissions, which cannot be met in sufficient volumes from point source capture.
- DAC technology is still challenged by high energy penalty, low capture rates and application at large scale.
  - Reaching the high capture volumes from DAC in 2050 will require research focus and fast maturing of the technology to reach the implementation of large-scale facilities on time for 2050 reductions.
  - As comparison, the biggest DAC hubs in the USA are currently targeting 1Mtpa. European projects are looking at 36,000 tons.
- At the same time, the scenarios have a strong focus on the delivery of negative emissions from DACCS.
  - DACCS is supposed to deliver ~2.5-5Mtpa negative emissions in 2050 in scenarios with strong focus on CCS application.
  - This underlines the need for more research and faster maturing of DAC(CS) technology especially in a 2050 perspective.
  - DACCS is not assumed to deliver negative emission in 2030.
- The implementation of DACC(S/U) technologies will require the availability of sufficient renewable energy.
- The EU scenario assumes application of DAC from 2040 building up capacities towards 2050.

→ **There is also a strong focus on the application of pyrolysis (for production of e.g. biochar) in scenarios building on enhanced application of CCS solutions.**

- Biochar has today a TRL of 6-7 which results in a forecast of reaching TRL 9 in 2030 at a normal technology development rate. In scenarios with strong CCS focus, it is assumed that pyrolysis should deliver ~1-2.5Mt negative emissions in 2030 – which potentially exceeds the currently assumed technical potential for biochar of 1.7Mt in 2030. This would require a large-scale application before 2030 to achieve the required emission for the 70% target.
  - To reach high negative emission reduction from biochar in 2030 therefore requires a faster TRL development through dedicated research and innovation.
- In 2050, pyrolysis is supposed to deliver ~1.5-2Mtpa which illustrates a continues need for biochar application and the refinement of the technology also beyond 2030.
- The enhanced application of biochar requires the availability of sufficient biomass, which is a scarce resource. Moreover, it requires sufficient land areal for application and an improved assessment of implementation practices and synergies with the agricultural sector.

→ **In the 2050 scenarios with higher reductions from agriculture and land use, a bigger amount of afforestation is applied to deliver the remaining negative emissions needed.**

- The new marked scenario assumes the biggest share with ~3Mtpa, which is a high volume considering that the technical reduction potential from afforestation in 2030 is estimated to 0.5Mt.
- This scenario would therefore require stronger research and implementation efforts into afforestation to reach the assumed capacities in the 2050, considering that forests need time to grow to capture at full capacity.
- This scenario would require utilisation of substantial areas of land, which is in competition for other land use and agricultural activities.

→ **Regarding CO_2 utilisation, the DEA scenarios have a strong focus on CO_2 application in green fuels. The utilisation in materials and chemical is not specified.**

- This underlines the research demand for CO_2 utilisation regarding emission reduction potentials and the development of a bigger variety of solutions to ensure the establishment of an atmospheric CO_2 cycle up to 2050.
- EU scenarios assume that emission reductions from CO_2 utilisation in materials and chemicals will only get realised in 2050. The scenarios also assume the biggest share in utilisation reductions to come from green fuels.

Societal Coupling

Societal Coupling

Societal Coupling covers targeted initiatives towards minimising uncertainty and mitigating risks within the CCUS sector. Achieving success in this sector requires not only technological advancements and innovation but also achieving public acceptance, along with establishing suitable economic, regulatory, and business models, as well as policy frameworks. The integration of CCUS into the broader energy system and decarbonisation targets is crucial to make the sector a sustainable and economically viable solution for emission reductions. Joint efforts are needed to coordinate development on both the supply and demand sides to secure political and public backing. There are several factors which influence this process:

CO_2 price and revenue streams

With increasing demand for emission reductions and the parallel development of CO_2 utilisation solutions, CO_2 becomes a tradable commodity on a fast-evolving carbon market. The development of the ETS (European Emission Trading System) is seen as the main determinant for the CO_2 price, where allowances are traded and thereby set a market-based price for CO_2. The price of the ETS is, among other factors, driven by the constant reduction of free allowances for emissions which will be phased out by 2034 and the extension of the range of sectors and companies covered by the ETS.

With regards to biogenic CO_2, the price is mainly determined by the voluntary market for carbon credits, driven by the supply of credits and technology costs for specific solutions. This is especially relevant for carbon removal solutions like afforestation or biochar since these emission reductions are currently not regulated by the ETS. However, the voluntary market is highly dependent on reliable certification of biogenic CO_2. It is also being considered to integrate the voluntary carbon market into the ETS. Recent projects like Ørsted Kalundborg CO_2 Hub have demonstrated that the offset of carbon credits represents an important cornerstone in the CCUS business case. It is therefore material for future bankability of CCUS projects to establish a robust and reliable carbon credit market. Another potential revenue stream is to sell biogenic CO_2 directly to offtakers for transforming the CO_2 into utilisation products as outlined in the chapter on CO_2 utilisation solutions. The establishment of a reliable voluntary market for biogenic CO_2 becomes even more relevant, when considering that the Danish 2030 & 2050 scenarios are heavily reliant on negative emissions from BECCS and DACCS. It is essential to ensure a reliable business case around negative emissions to realise the assumed capture and storage volumes in 2030 and 2050.

When considering current costs of CCS (figure 6 in appendix 1) a permanent ETS above EUR 100 (in a low-price scenario) is needed to ensure a market incentive strong enough to establish CCS without subsidies. At the beginning of 2023, the ETS exceeded a level of EUR 100 for the first time. Since then, geopolitical factors have caused a volatile ETS with price losses below EUR 60 in the beginning of 2024. Long term forecasts assume however a stabile price increase up to EUR 100 in 2030. The introduced price floor of EUR 100 by the Danish CO_2 tax supports a stable CO_2 price in a national context from 2025. The development of the ETS is essential to make CCUS economically viable and to achieve sufficient emission reductions through the implementation of the technology. In return, it is essential to decrease CAPEX and OPEX costs of CCUS through further innovation to ensure the establishment of a market-based industry.

Business case and investments

The business case for CCUS is still under development and subject to many uncertainties. The central elements for the business case are:

Figure 46: Central elements of the business case

<table>
<tr><th>CO_2 capture</th><th>CO_2 transport</th><th>CO_2 storage</th></tr>
<tr><td>Compensation for CO_2 avoidance</td><td>Tariff for CO_2 transport</td><td>Tariff for CO_2 storage</td></tr>
<tr><td>Volumes of CO_2 capture</td><td>Volume of CO_2 transport</td><td>Volume of CO_2 stored</td></tr>
<tr><td>CO_2 capture CAPEX</td><td>CO_2 transport CAPEX</td><td>CO_2 storage OPEX</td></tr>
<tr><td>CO_2 capture OPEX</td><td rowspan="2">CO_2 transport OPEX</td><td>Decommissioning liabilities</td></tr>
<tr><td>(Carbon credits for biogenic CO_2)</td><td>CO_2 storage liabilities</td></tr>
<tr><td colspan="3">Available public funding (amount & penalties)</td></tr>
</table>

The development of the above variables is difficult to forecast, which constitutes a challenge for the attraction of investments and loans for CCUS projects. A common mechanism to attract investments is the securing of long-term offtake contracts, which is a challenge in an evolving market, where all parts of the value chain are still under development.

The components and influencing factors for the business case differ a lot along the value chain. Where the implementation of the technology is an expense for emitters (at least regarding fossil CO_2), storage and infrastructure operators earn on the handling of CO_2 as a commodity and try to secure large volumes of CO_2. Denmark's storage capacity exceeds the national volumes of CO_2 available for CCS by far. This is why large storage operators in Denmark do not only consider acquisition of CO_2 from domestic emitters but are also dependent on the import of foreign CO_2 to establish a business case. This is a relevant factor for the building of consortia along value chain. Depending on the supply and demand of CO_2, this can lead to storage of Danish CO_2 abroad and import of foreign CO_2 to be stored or utilised in Denmark.

Then again there is a different foundation for business cases for the operation of DAC facilities or the application of NbSs like biochar or afforestation. These capture solutions generate negative emissions and can thereby create revenue through the sale of carbon credits.

Value chain development

The CCUS market is in its early establishment phase and the first full value chain projects like the Ørsted Kalundborg CO_2 Hub are under development in Denmark. It remains a challenge for all actors along the value chain (emitters, infrastructure operators, storage operators, utilisation facilities, potential third-party project developers) to figure out configurations for project consortia, necessary agreements and modes of working together.

To illustrate the complexity of choices, this is an example for potential models from an emitter perspective are:

→ **Option 1:** The emitter guarantees the entire value chain through subcontracting, financing it with equity injection from the emitter along with commercial loans.
→ **Option 2:** The capture project involves partial private ownership, allowing for private investment opportunities and the incorporation of expertise from project developers or business partners from different sectors of the value chain.
→ **Option 3:** The emitter commits to establishing a new carbon capture facility, including financing, but will collaborate closely with a business partner to secure the remaining aspects of the value chain.

It is important for the building of the business case to better understand the risk structures, different business cases and revenue streams along the value chain. In order to build consortia, it is important to couple different value chain models with investment potentials. CCUS projects can be owned and established as part of the emitter company. However, there are other models available like the establishment of a project financing, where all risks and all gains are shared along the entire value chain. This usually also increases the interest rates for potential loans substantially since the overall dependencies within the value chain and the liability is shared among several parties, which makes the investment riskier. Another factor in the value chain establishment is that different emitters have different restrictions depending on for instance state ownership or an independent entity.[100]

Public acceptance

Public acceptance is critical for the successful implementation of CCUS technologies, playing a central role in influencing various aspects of project development. Without community backing, projects may encounter regulatory obstacles and delays, jeopardising their feasibility. Secondly, attaining social acceptance to operate within local communities is essential, as CCUS projects often rely on access to land, infrastructure and resources. Establishing trust and confidence among community members is crucial, as it fosters cooperation and minimises opposition. Public acceptance helps cultivate trust in CCUS technologies and initiatives, reassuring communities about their safety, efficiency and overall benefits. This trust, in turn, can influence governmental policies and funding decisions, with policymakers more inclined to prioritise and invest in CCUS, when they align with public interests and preferences.

100 Finansiering+af+CCS.pdf (squarespace.com)

In Denmark, public acceptance of CCUS shows different dynamics. While the country presents relatively high support for CCUS (69%)[101] compared to other nations, distinct preferences and concerns shape the landscape. Danish respondents express a clear preference for domestic CCS and CCU value chains, emphasising a desire for self-sufficiency and control over environmental efforts[102]. Concerns also persist regarding the potential prolonging of fossil fuel use through CCUS, signaling reservations about its alignment with broader sustainability objectives. Acceptance of CCS appears to be influenced by location, with offshore CCS preferred over nearshore and onshore alternatives. Furthermore, media framing emerges as a crucial factor as it potentially enhances support for CCS initiatives[103]. Understanding these intricacies is paramount for effective engagement and communication strategies aimed at addressing concerns and fostering trust in Danish CCS projects.

Despite the significance of public acceptance, there remain several knowledge gaps that warrant further exploration. Understanding the underlying reasons behind location preferences and disparities in acceptance levels across different communities is crucial for informing siting decisions and devising effective engagement strategies. Additionally, addressing safety concerns related to CO_2 transport, storage, and potential environmental impacts requires in-depth research and effective risk communication strategies[104]. Moreover, assessing the role of clear and transparent regulatory frameworks in building public trust and acceptance of CCUS projects is imperative for facilitating their development and deployment[5]. Equally important is investigating the efficiency of community engagement methods and dialogue processes in fostering meaningful participation and collaboration between project stakeholders and local residents[105,106]. Lastly, understanding how different media frames shape public perceptions of CCUS can inform communication strategies and outreach efforts aimed at enhancing public support[107].

Digital technologies

Logistics, monitoring and trust in the CCUS value chain can only be achieved with an efficient, transparent and safe digital infrastructure. Capture, storage and use of CO_2 involves coordination of many processes with high complexity, critically relying on digital technology research and innovation in areas like:

- → Real-time secure monitoring, forecasting, control of conversion and storage processes in highly fluctuating production and consumption scenarios. Research and innovation in IoT, cyber-security, digital twins and program verification is necessary.
- → All units in the conversion process must be managed and coordinated in real time by means of models and algorithms providing reliable forecasts based on present data. Research and innovation in efficient distributed data management, computer vision and machine learning are necessary.
- → The CCUS materials are intangible and hard to measure. New digital models, algorithms and interfaces need to be developed to create trust and deliver transparent and traceable measures of carbon that can be used as a basis for a dynamic price model for CO_2. Research and innovation in data modelling, info visualisation, optimisation, game theories and blockchains is necessary.
- → Using CO_2 in the energy grid requires digital models that always keep the smart grid in balance within sub-second reaction time. This grid modelling and control become more advanced when more renewable components with different characteristics are added. Research and innovation in distributed systems and coordination without a center of complete knowledge is necessary.

The digital research and innovation will be integrated with chemical, physical and geological solutions. Moreover, a close coupling to the energy sector is facilitated. The research will produce generic computer science results on methods, as well as interdisciplinary results with the other CCUS research disciplines.

Developing CCUS with novel digital solutions has great business potential both nationally and internationally. Denmark has unique strongholds within digital research where the IFD DIREC center, NNF Data Science Academy and the Pioneer center in AI (DNRF and more), can contribute with competences and results to be tailored to CCUS.

101 https://www.ifw-kiel.de/publications/carbon-capture-and-storage-publics-in-five-countries-around-the-north-sea-prefer-to-do-it-on-their-own-territory-31758/
102 https://www.ifw-kiel.de/publications/carbon-capture-and-storage-publics-in-five-countries-around-the-north-sea-prefer-to-do-it-on-their-own-territory-31758/
103 https://www.sciencedirect.com/science/article/pii/S2214629624000434?via%3Dihub
104 https://open.substack.com/pub/greenbarrel/p/class-vi-primacy-states-risks-to?r=27b3ch&utm_campaign=post&utm_medium=web&showWelcomeOnShare=true
105 https://open.substack.com/pub/greenbarrel/p/class-vi-primacy-states-risks-to?r=27b3ch&utm_campaign=post&utm_medium=web&showWelcomeOnShare=true
106 https://open.substack.com/pub/greenbarrel/p/exploring-public-opposition-to-ccus?r=27b3ch&utm_campaign=post&utm_medium=web&showWelcomeOnShare=true
107 https://www.sciencedirect.com/science/article/pii/S2214629624000434?via%3Dihub

Integration through modelling

It is critical to develop multi-scale integrated modelling capacities for exposing efficient deployment pathways and predicting their effects on CCUS. These modelling capacities must be trans-technical and incorporate both CO_2 uptake and emission from capture, use and storage. Further, it must include economic modelling at both business and societal level, to integrate effects of regulation and market development, while identifying spill-over effects to other sectors. To assess the necessary effect on climate, modelling must address, and help us understand, the long-term stability of carbon storage in biomass, soils and materials and how natural processes in the atmosphere-biosphere-ocean system recycle CO_2 on human as well as geological time scales. Upscaled models must link to the global carbon cycle via earth system and climate models as well as to global economic trade models. This will allow insights into the global effects of carbon capture, use and storage on future climate, and help guide the necessary balance between carbon storage and carbon use over time.

Respecting environment and biodiversity

The implementation of a biogenic CO_2 cycle is reliant on the availability of atmospheric carbon derived from biomass and DAC. Biomass is unlikely to sufficiently deliver all the carbon needed. Hence, the demand for new biomass and thereby also land, which at the same time delivers food, nature and recreative means, will be a critical point. It is crucial that the supply of biomass will be sustainable and respects our responsibility to protect environmental conditions and biodiversity.

Assessment of Social Readiness Level

Denmark's overall SSRLE is estimated to be around 6, approaching SSRLE 7. This assessment is based on the level of regulation implemented, as described in the chapter on CCUS status in Denmark and the EU, as well as the necessary research on societal coupling outlined in this chapter. Currently, CCUS technologies are undergoing testing, with the first full value chain projects already in implementation phase. Efforts to gain public acceptance are underway, including public hearings and information meetings. The next crucial step involves developing a plan for societal adaptation to further integrate these technologies.

Conclusions

→ **Denmark is assumed to have an overall SSRLE of 6 on the threshold to SSRLE 7 with several CCUS projects under development and implementation and public acceptance initiatives being conducted.**

- As a next step, societal adaptation plan should be developed.

→ **At a European level, the ETS is the most central pricing mechanism for CO_2 and thereby vital for the future development and implementation of CCUS. At a national level, the Danish CO_2 tax provides a stabilising supplement from 2025 also for industries not covered by the ETS.**

- Strategies for building a more robust and reliable voluntary carbon market for biogenic CO_2 have to be assessed in conjunction with advantages and disadvantages of an integration into the EU ETS.
- It is important to investigate different determinants and drivers for CO_2 prices.
- The voluntary carbon market operates at global level for the offset of carbon credits. This is currently a central market for the trading of credits from biogenic CO_2. Due to Denmark's high capture potential for biogenic CO_2, the reliability and stability of the voluntary carbon market should be further researched and supported.

→ **The CCUS business case is still evolving, and revenue streams differ depending on the actors along the value chain, applied CCUS solutions and the origin of CO_2.**

- There is a need for developing alternative business models for CCUS focusing on what activities can be subject to markets and which parts should be subjected to economic regulation. This work should also explore potentials for new services & business cases.

→ **Different market drivers for the actors along the CCUS value chain may lead to inefficiencies in CO_2 allocation/ storage location (e.g., storing of CO_2 abroad) from an economical and climate perspective.**
- Further research should look into how different parts of the value chain and different financing models impact the bankability of CCUS projects and how risks can be mitigated to increase investments in CCUS projects. For this, it is useful to learn from development of other and comparable infrastructure industries.

→ **Public acceptance is a central enabler for CCUS projects. First studies in the field indicate more acceptance for offshore storage compared to onshore storage and national CCUS value chains compared to foreign CO_2.**
- Based on first studies, Denmark seems to enjoy comparably strong support for CCUs (69%).
- In terms of public acceptance, understanding the underlying reasons behind location preferences and disparities in acceptance levels across different communities is crucial for informing siting decisions and planning effective engagement strategies.
- Equally important is investigating the effectiveness of community engagement methods and dialogue processes in fostering meaningful participation and collaboration between project stakeholders and local residents.
- There is also the need for surveys to collect useful data on public sentiments regarding perceived risks and attitudes along the value chain, technologies, support mechanisms, distribution of costs and benefits, etc.
- Comprehending how different media frames shape public perceptions of CCUS can inform communication strategies and outreach efforts aimed at enhancing public support.

→ **Digital solutions & infrastructure are important to ensure a safe and transparent operation of CCUS value chains.**
- Research and innovation in IoT, cyber-security, digital twins and program verification is necessary.
- Research and innovation in efficient distributed data management, computer vision and machine learning are necessary.

→ **Digital solutions are an important tool for integrating CCUS in the broader energy system and their development yields strong business potentials.**
- Research and innovation in data modelling, info visualisation, optimisation, game theories and blockchains is necessary.
- Multi-scale integrated modelling capacities are crucial for the analysis of efficient deployment pathways and effects of CCUS.

→ **The development and implementation of CCUS has to take place in accordance with environmental and biodiversity standards.**

Links to other innomission roadmaps and partnerships

The CCUS roadmap cannot be viewed in isolation. CCUS research started out as a relatively straight-forward challenge of removing fossil carbon from industrial point sources. However, as this roadmap demonstrates, the implementation of CCUS has strong impacts far beyond the fossil-based point sources with a strong focus on capture of biogenic and atmospheric CO_2 to reach the 2030 and 2050 climate targets. There are major overlaps to other Innomissions focused on “Green fuels”, “Agriculture and food” and “Circular economy”. Obvious overlaps are identified with the mission on green fuels as capture of biogenic CO_2 from the CCUS roadmap will feed the power-to-x activities. Overlaps with the mission on climate friendly agriculture occur because biological storage will involve and possibly impact agricultural activities. Moreover, the need for biogenic carbon will require land and thereby interact with other land-focussed missions. Finally, there are overlaps with circular economy of plastics and textiles because CCU will feed future production of plastics and materials. A coordinated effort across the roadmaps is therefore essential and will be an important task for the four partnerships.

Denmark: Direction 2050: Danish CCUS Roadmap 2024