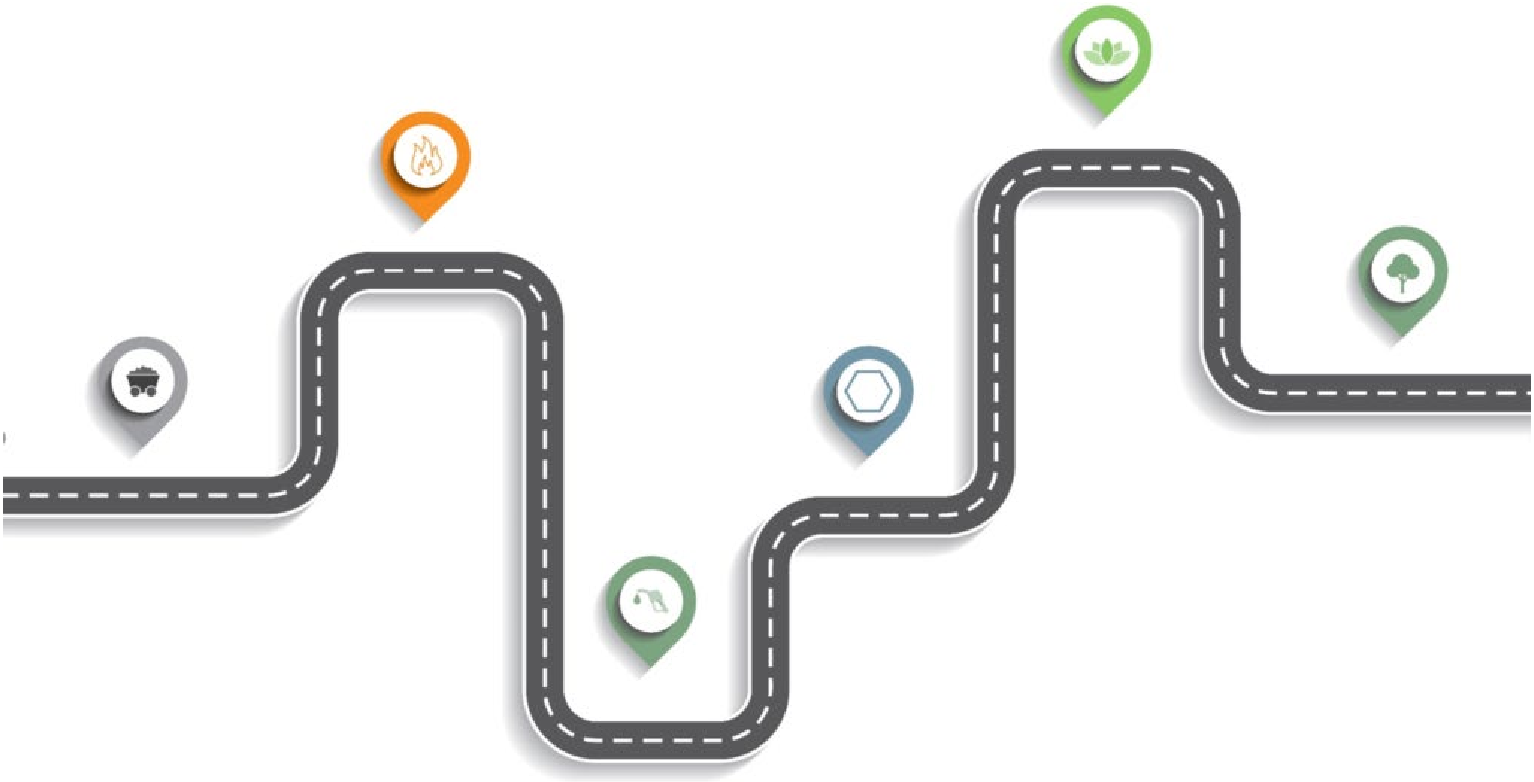
The CCUS Roadmap



Content

CCUS Roadmap for Innomission 1

1 Vision

The vision for the present roadmap is to achieve a fundamental change in the way we view, value, and use carbon resources. We envision to capture and store current fossil and biogenic CO_2 emissions, while simultaneously implementing a complete switch from fossil-based to biogenic supplies derived from the natural carbon cycle. By envision the long-term goal – from 2050 and beyond - the roadmap strives to demonstrate how CCUS can be the key to balances the short-term urgent needs for fossil-based CCS technologies with the long-term biogenic based CCUS-plan that delivers globally scalable and innovative solutions to the carbon needs of the society. By focusing on the long-term needs, the aim is to avoid those solutions to the 2030 goal of 70% emission reduction creates a technological "lock in", with massive short-term investments in technology and infrastructure becoming obstacles to the long-term goal. Finally, through integration of business-, human- and social-sciences and a focus on the final goals, our vision is to outline solutions that generate a wealth of new industries, export opportunities, growth, and jobs.

CCUS is critical for reaching the goals of 70% emission reduction in 2030 and net-zero emissions in 2050. It is also critical, as pointed out by the IPCC, to reduce atmospheric CO_2-concentrations through net-negative emissions in decades to centuries after 2050 in order to prevent long-term global warming beyond 1,5-2°C.

Key deliveries of the CCUS partnership by fulfilling of this roadmap

- Crucial contributions to the goal of 70% CO_2-reduction by 2030, carbon neutrality by 2050, and long-term negative emissions beyond 2050, while still ensuring the necessary carbon supply to society. The technical potential in 2030 is up to 7-15 Mt CO_2 captured per year in 2030 (50-80% of the emission gap to reach the 70% target) and in 2050 up to 6 ton CO_2 can be captured and supplied to the production of green fuels and products.
- Technologies, tools and pathways to limit emissions to the atmosphere in both short and long term by gradual, but fast, switching from the current fossil-based carbon supply to a green supply based on the atmosphere to deliver the carbon needed in the society, combining permanent storage and smart utilisation of carbon resources.
- Multiple green pathways for carbon from the natural carbon cycle to enter the societal carbon use through a combination of large, small and scalable innovative solutions and the build-up of new technologies and companies with a significant national and international business potential.
- Outlines and timelines of the research and development needed for the individual technologies, as well as the systems integration based on existing knowledge, Danish strongholds and strong partnerships between universities, technological service providers, large and small companies, and societal stakeholders.
- Awareness and solutions to urgent societal readiness steps needed at the legal, regulating, economic and political level as well as externalities necessary to implement the changes without compromising key sustainability, environmental, biodiversity and human conditions. This includes an overall systemic view and collaboration with land aspects, as priorities of "land" for food, fibre, CCS, biodiversity etc. is likely going to become a constraint.

Long-term strategies without short-term "lock in"

The implementation of the CCUS roadmap must facilitate both the short-term 70% CO2 emission reduction by 2030 and the next and even more challenging step to reduce to net-zero and below by and after 2050. Therefore, the here-and-now actions based on high-TRL technologies must be urgently brought into play at the unavoidable fossil-based emission sources, while also allowing for the onset of the longer, more visionary, and innovative perspectives of green CCUS. Importantly, we must ensure that high investments in technologies and infrastructures for the short-term solutions are scaled capacity-wise to the long-term needs and perspectives in order not to become obstacles to the long-term solutions.

Therefore, by bridging the short-term (2030) and long-term (2050) perspectives, this CCUS roadmap facilitates a relatively short way to a fossil-free CO2 future and to business and technology innovation beyond what we know today. Furthermore, the roadmap addresses how a sustainable implementation of technological solutions can be achieved by (1) obtaining the necessary levels of societal readiness, e.g., through regulatory and financial instruments, as well as (2) protecting biodiversity and the environment. A systems-based, technology-agnostic approach, in which sector coupling and scalability play vital roles, is of key importance to the implementation of our roadmap.

Taking carbon from black to green

Currently, large amounts of fossil hydrocarbons are used to cover the societal needs for energy and chemicals. These hydrocarbons flow linearly from subsurface extraction through societal utilization into CO_2 emissions to the atmosphere. A sustainable fossil future involves a relatively near end this linear flow, and a transformed view of CO_2 as a valuable, and limited, resource in a circular carbon economy. It is not possible to continue current fossil carbon extraction and use, while maintaining a stable atmospheric CO_2 concentration through CCS only. Not even if the CCS includes net negative emission in terms of bio-based CO2 storage. We therefore over the years from now to 2030 have to limit fossil-based carbon sources to a minimum, start the out phasing of carbon from the energy streams in society and plan the long-term net negative emission storage to compensate for that. Further, we have to allow atmospheric CO_2 to become the main supply for societal carbon needs in chemicals, materials and to some extent fuels.

Phasing out extraction of fossil-based carbon will in itself reduce the emissions to the atmosphere. At the same time, it makes atmospheric CO_2 the only CO_2 source, thereby creating a pull for atmospheric CO_2 for capture and utilization. In the short term, this will be an important steppingstone to a CO_2-neutral future with little or no extraction of fossil carbon. In the longer term, it will lead to a net-negative state based on utilization and storage of atmospheric CO_2. Consequently, over the course of the roadmap, carbon will switch from fossil sources (current state) to atmospheric sources (future green state) in a circular utilization that recycles atmospheric carbon to industry and fuels, but continuously captures more than is recycled.

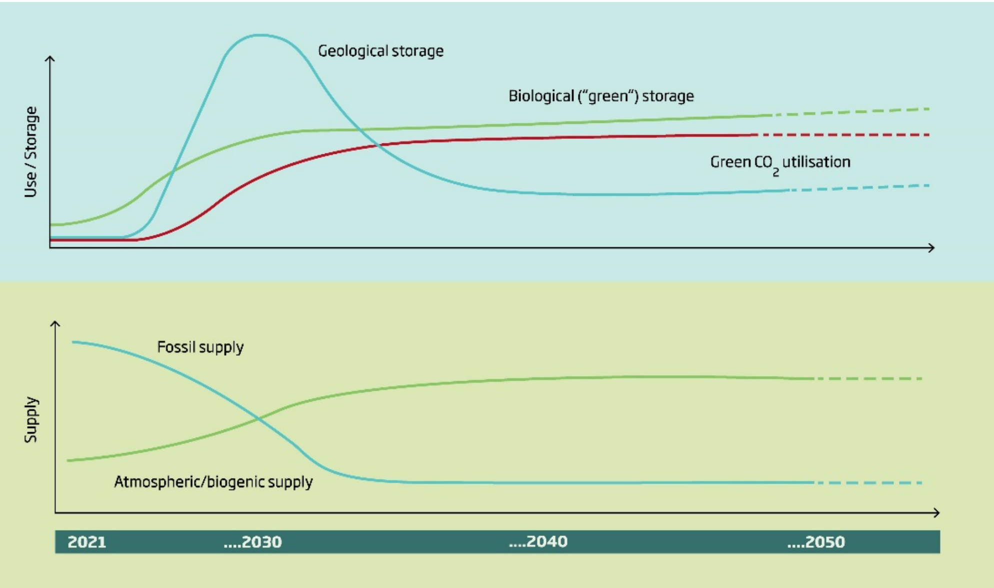


Fig. 1.1: Future annual CO2 flow rates of CCS and CCU

Combining storage and utilization of carbon with targeted impact

The switch from black (fossil-based) to green carbon tracks involves two simultaneous and complementary strategies regarding CCS and CCU. One is our current high fossil-based CO_2 emissions calling for immediate CCS action focused on a few large emission sources. The second and meanwhile, is a complementary green strategy, developing smart technologies and pathways to capture and use the atmospheric CO_2 as the main CO_2 source. These strategies have to be pursued side by side and share a number of features and technologies, especially geological storage, which is continuously needed for providing short-term emission reduction in 2030 and net-negative emissions in 2050 and beyond. The two approaches will switch importance in the coming few decades, with a pre-dominant but eventually retracting role of fossil-based CCS, and a steadily growing significance of CCS and CCU based on atmospheric sources (Fig. 1.1).

The green path in this CCUS roadmap is the only way to provide the carbon needed for societal activities in a fossil-free CO_2 future. It builds on a wide range of carbon-capture technologies, from nature's own mechanisms in biomass (photosynthesis) and minerals, to direct capture from industrial point sources and from the atmosphere (Fig. 1.2). The balance between storage and utilization of CO_2 will develop over time as technologies and industries mature and grow. The early phase (2020-2030) has a strong focus on combining capture from industrial point sources with geological storage, but it also involves natural CO_2-storing processes by photosynthesis in biomass and soils (including biochar), as well as innovative CCU projects and utilization for fuels (Power-to-X) or chemicals. The early phase will gradually transfer into the long-term phase (2030-2050) where the society's need for carbon will be reduced, as energy is increasingly supplied by wind, solar and geothermal sources. Then fossil carbon sources will be replaced by new and innovative technologies extracting carbon directly from the atmosphere (using sustainable biogenic sources or direct air capture) to provide chemicals, materials, and some fuels.

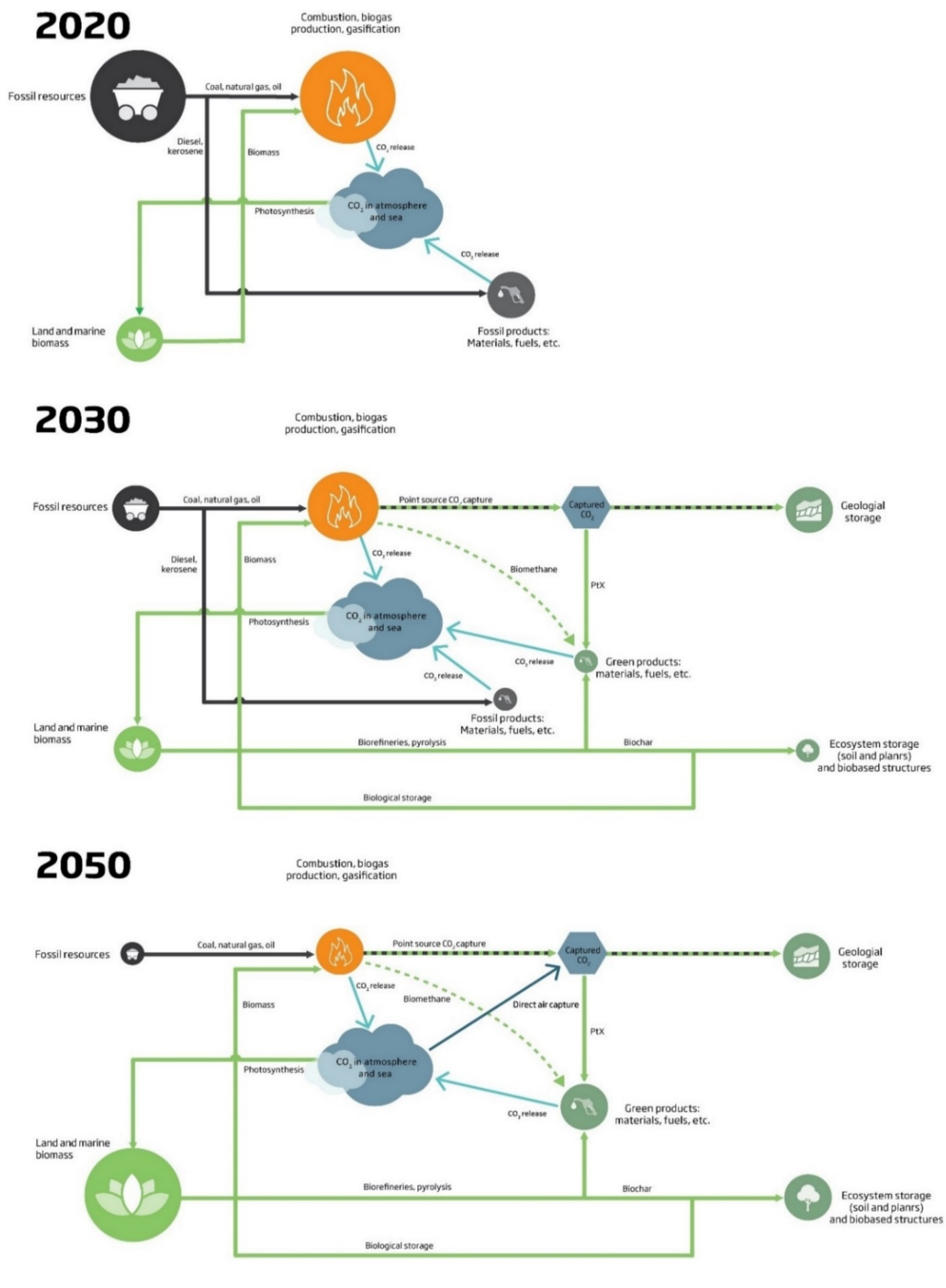


Figure 1.2: The change of CO2 flow from fossil to atmospheric CO2. The size of the icons depicts the increase/decrease in yearly amounts

For the CCUS roadmap, several challenges related to basic geological, chemical and biological understanding, systems integration, as well as assuring societal readiness to adopt the new solutions and sustaining environment and biodiversity remain. In particular, legislation and valorization of CO_2 and economic incentives for different sectors are currently main barriers. Overall, solutions must be found by combining technical aspects with sector coupling and economics, social sciences, and humanities in a holistic approach. It is worth pointing out, that the main obstacle for a CO_2-neutral future is likely not lack of technology, but lack of economic drivers.

Fig. 1.3: Elements that the roadmap is built upon

2 Links to other Innomission roadmaps and partnerships

The CCUS roadmap cannot be viewed in isolation. The CCUS challenge 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, and major overlaps can be identified with the other missions focused on “Green fuels”, “Agriculture and food” and “Circular economy”. Obvious overlaps are identified with the mission on green fuels as carbon capture from the CCUS roadmap will feed the Power-to-X activities, with the mission on climate friendly agriculture because biological storage will involve and possibly impact agricultural activities and because the need for biobased carbon will require land and thereby interact with other land-focussed missions, and finally with circular economy of plastics and textiles because CCU will feed future use of plastics and materials. A coordinated effort across the roadmaps is therefore essential and will be an important task for the four future partnerships.

3 Strongholds: State-of-the-art and beyond

3.1 The global position of CCUS

More than 110 countries globally have pledged to get to net-zero emissions in the next 30 years, and there is considerable political attention to the urgent need for reductions of current greenhouse gas emission as well as CO2 removal from the atmosphere. CCUS is a known technology. It spans from technology-intensive capturing of CO2 from large industry, Direct Air Capture (DAC), and pure biological capture methods such as large-scale afforestation and marine biomass to storing the CO2 permanently in the underground, in minerals or soil, or utilising the CO2 for production of materials or fuels.

Besides Denmark a handful of countries (Norway, The Netherlands, United Kingdom, Canada and Germany) are at the forefront of the CCS industry, working with capture from large point sources and storage in geological reservoirs. Here CO2 capture is applied on a large scale in fossil industry to produce CO2 emission free electricity or natural gas. This includes a limited number of sites e.g., the Boundary Dam electricity site (1 Mtpa) or the Shute Creek natural gas processing site (5 Mtpa). These processes are today driven by solvent-based principles. A patented energy intensive technology dating back to the 1920’s. Storage of CO2 in deep offshore geological formations is a proven technology. Since 1996, Norway has stored CO2 in saline formations at the North Sea field Sleipner. The Sleipner CCS facility has injected over 20 Mt of CO2. The facility was the first use of CCS as climate mitigation tool within a commercial operation. Since Sleipner, four commercial operations storing CO2 in saline formations and numerous demonstration projects have been initiated around the globe. Currently, some 28 CCS projects are active globally. In 2020, these projects captured and stored a total of 40 Mtpa of CO2.

Other alternatives are Direct Air Capture (DAC) or Bio Energy systems (BECCS), like pyrolysis, afforestation and uptake in marine biomass. These technologies are currently being tested at small scale prototypes or their full potential in CCUS is being explored.

The annual use of CO2 in the world is in the order of 2-300 Mt/year CO2, of which most is used in the fertilizer industry and only a minor part is used in the food industry. By far the largest direct use of CO2 without conversion is through underground storage in connection to enhanced oil recovery (EOR). This could easily change if CO2 becomes a commodity chemical for large industry, e.g., in the plastics, chemicals, and fuels market.

3.2 The national position of CCUS

The Climate Program by the Danish Government 2021 states potentials of multiple methods for reducing CO2 emissions including expected potential contributions towards 2030. For the CCUS technologies the potential contribution is 7-15 Mt/year. The numbers estimated by the Danish Government are based on available CO2 sources in Denmark, however, the geological storage potential of the Danish underground is considerably larger and can potentially be used for storing captured CO2 from other countries.

In Denmark we have the right competences in terms of excellent research, an industry with relevant strongholds and modern infrastructure to make it realistic, that CCUS can be a driver for growth and employment across numerous value chains, e.g., carbon capture from existing large combustion facilities and from biogas upgrading, carbon storage in depleted oil and gas fields or new geological structures, and utilisation of carbon from CO2.

The Danish Climate Agreement of 22 June 2020 paved the road for the megaton implementation of CCS by developing a marked-based pool for 0.4 Mt/year in 2025 and 0.9 Mt/year by 2030. Currently, the North Sea Nini West field is being matured for CO2 storage, and the field obtained a certification of feasibility in 2020.

Further, Denmark has significant position in the CCUS transition, which will provide solutions to the global CO_2-challenge. Innovations within utilization of CO_2 for fuels, chemicals and materials are currently booming, and enormous potentials exist for building a future Danish industry delivering non-fossil and green solutions globally, while creating jobs and growth in Denmark. Likewise, Denmark has huge potentials for large-scale geological storage, not only due to the many promising reservoirs in and around the North Sea area, but also due to the extensive knowhow gained over decades with advanced oil- and gas-exploration. By pairing university-based research with open-science platforms for innovation with industries, Denmark has a huge potential to bring capture-and-storage technologies, chemical CO_2 conversion, biorefinery and life sciences into play. It paves the way for systemically re-thinking the regulatory regimes and framework conditions, transfers the challenges of scaling into a common ambition and guides a broad, yet tangible capability of Danish CCUS stakeholders. This roadmap provides a vision and outlines activities to tackle these fundamental challenges and provide the important coupling between short-term (2030) and long-term (2050) goals.

Fig. 3.1 highlights the many Danish research areas and technical strongholds of relevance for CCCUS, where some are at early stage of mission-driven research (low TRL), while others are close to commercialisation (high TRL).

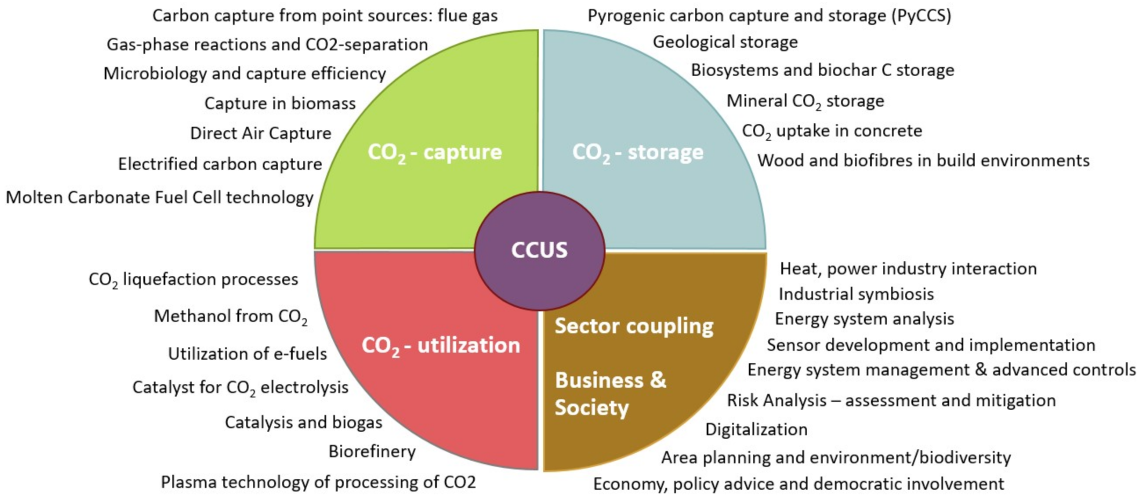


Fig. 3.1: Danish strongholds within research and innovation

4 CCUS Potentials

In conjunction with other CO_2-emission reduction initiatives CCUS is a relevant tool in Denmark to abate emissions from hard-to-reduce processes and either provide permanent CO_2 storage (CCS) or provide non-fossil carbon-based fuels and products (CCU).

The greenhouse gas emission reduction goals set by the Danish government aim at reducing the greenhouse gas emission by 70 % in 2030 compared to 1990 emission levels and reaching net-zero emissions by 2050. The current status is shown in Fig. 4.1.

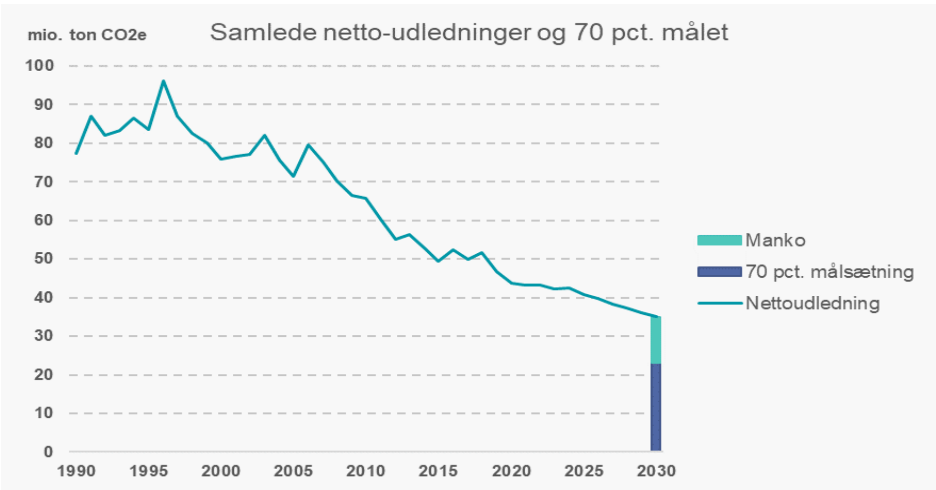


Figure 4.1: Current status of 70% goal. Source: ENS Klimastatus og fremskrivninger, April 2021

4.1 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 (aka. non-fossil) such as biomass, the collected CO_2 has just recently been removed from the atmosphere and storing of the collected CO_2 will thus result in a net removal of CO_2 from the atmosphere. Accordingly, sequestration of fossil CO_2 can facilitate carbon emission reductions, but in order 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 depicted in Fig. 4.2.

The CO_2-source must be verifiably sustainable. This means, for example, 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.

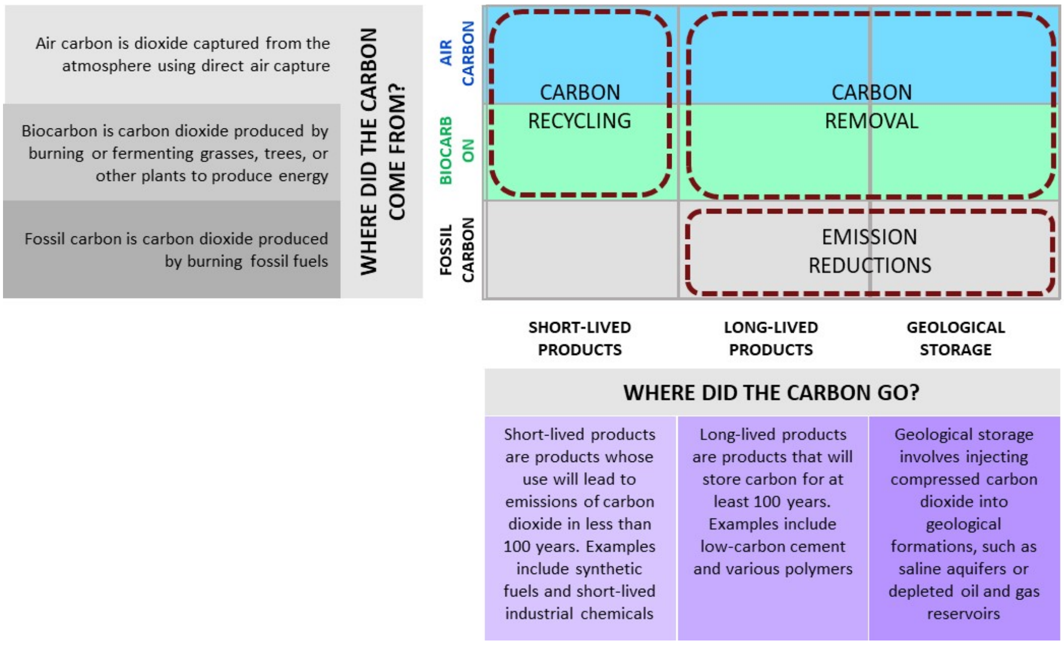


Figure 4.2: Reduce, Remove, Recycle: Clarifying the Overlap between Carbon Removal and CCUS, American University, 2020

4.1.1 Large CO_2 point sources

CO_2 is most feasibly collected from the largest point sources being power plants, waste incineration plants and cement plants. The relatively low cost per unit of mass of CO_2 means that logistics and easy transport of CO_2 are also relevant parameters to consider, which would favour large plants with direct access to ship transport.

The potential point sources are listed in Fig. 4.3 showing the expected maximum feasible volumes. Most of these point sources have access to the sea. The most feasible sources for initial projects will be newer waste incineration plants and biomass CHPs, where remaining technical lifetime is long and there is a steady annual emission volume, thereby giving rise to high capture plant utilisation, but noticeably the expected CO_2 emissions from waste incineration are expected to decrease with increased amounts of recycling in the future. With the increased electrification and use of renewable energy towards 2050, the point sources for CO_2 will be fewer and smaller.

The increased use of biomass in the Danish energy sector does per definition provide CO_2-neutral energy services and contributes significantly to the attained national CO_2-reductions, while biomass-based combined heat and power plants remain relevant point sources for carbon capture. Accordingly, there will still be relevant sites for carbon capture, even though the energy sector is expected to be almost CO_2-neutral by 2050.

CO_2 emissions from point sources (Mt CO_2e/year)	2017 emissions	2030 emission	2030 CC potentials	2050 emissions	2050 CC potentials
Waste incineration (fossil)	1,4	0,6	0,6	0,2	0,2
Waste incineration (renewable)	3,5	1,7	1,7	0,9	0,9
Large biomass power plants	2,9	3,3	2,5	1,7	1,5
Cement production	2,3	1,33	1,1	1,0	0,8
Refineries	2,7	2,3	1,1	0,7	0,4
Other heavy industry	1,6	1,6	0,4	0,8	0,2
Total large point source potentials			**7,4**		**3,9**
- of which is fossil CO_2			2,1		1,2

Fig. 4.3: Point sources for Carbon Capture. Data derived from "Basisfremskrivningen" and CO_2 neutral "affaldsenergi" 2030 and data from NIRAS/Danish Council on Climate Change. "Other heavy industry" covers the 20 largest industrial CO_2 emitters in Denmark except refineries. The 2050 data are best guesses based on expected electrification and efficiency improvement of the relevant sectors.

4.1.2 Alternative CO_2-sources

Other future alternative sources of CO_2 or other forms of carbon will come from smaller sources. The price of capturing CO_2 will be higher for smaller sources because of the lack of economy-of-scale and the increased unit cost for transport of CO_2. Smaller CO_2 point sources include district heating plants mainly running on biomass or biogas as well as emissions from medium size industries with own production of process heat. These types of CO_2-sources are also expected to decline as the energy services become electrified.

A significant alternative CO_2 source is from biogas, which is expected to be an increasingly important energy source for industry process heat as well as a building block for future carbon-based products. Raw biogas consists of roughly 60% methane and 40% CO_2. For now, a large part of this CO_2 is emitted through upgrading (i.e. purifying to CH_4 and releasing the CO_2) of biogas for injection of methane in the national natural-gas grid. However, this CO_2 source may also be collected and stored or utilised, or the biogas can be methanised through the addition of hydrogen. In this way the emission of CO_2 to the atmosphere is captured and the carbon is available as methane for direct use or further processing. The estimated amounts of possible methanation of biogas are estimated at 15 PJ/year in 2030 and 17 PJ/year in 2050[1]. This equals 0,9 Mt CO_2/year and 1,0 Mt CO_2/year, respectively.

The future demand for atmospheric carbon does not necessarily come in the form of CO_2, but could also be in other non-oxidized forms, depending on the use. An example is the aforementioned biogas upgrading where the biogenic carbon is collected as methane with the aid of hydrogen. Another route of long-term storage of carbon is in the form of biochar from pyrolysis, which Danish Council on Climate Change estimates at a 4 Mt/year potential in 2030 and which the Danish government suggest as >25% of the initiative for the agricultural emission reductions in 2030. Finally, biomass refined for targeted chemicals and structures or fibres for materials allows significant pathways for use and storage of carbon.

Atmospheric CO_2 can also be captured directly from the air for example by the direct use of technology or by enhancement of the CO_2 uptake capabilities ecosystems.

4.2 Future demand for carbon

A main focus point for reaching the climate goals is naturally ending the use of fossil fuels. This is well underway in the energy sector and in households but is expected to be difficult in the transport sector, for example in shipping and aviation, where requirements for energy density makes it challenging to utilize battery-electric or hydrogen solutions. Moreover, it is also expected that demands for carbon in other sectors will continue to exist in the future. The predominant future fuels for maritime and aerial transport are not yet known, as several options are available such as e-methanol, DME, hydrogen, ammonia, ethanol-based fuels and more. Other areas where renewable CO_2 can substitute fossil carbon is depicted in Fig. 4.4.

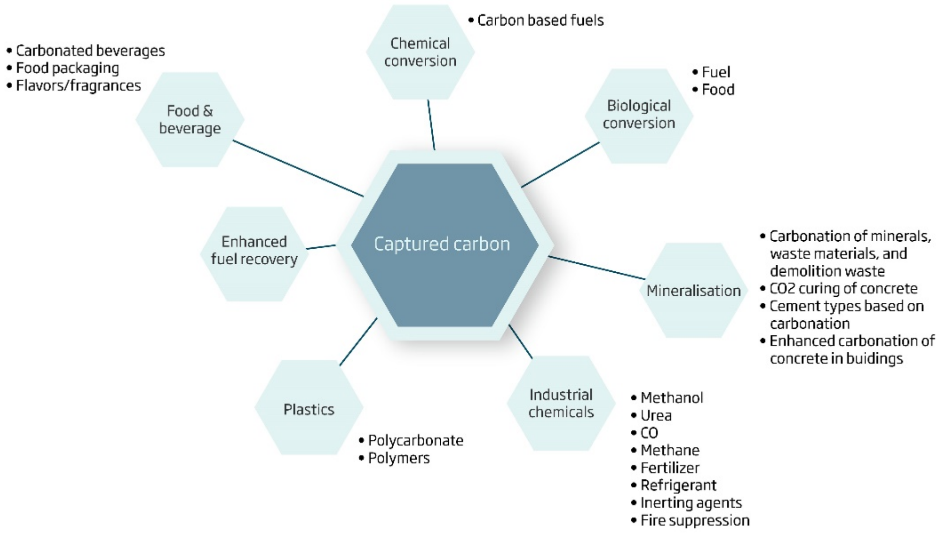


Fig. 4.4: Uses of captured carbon.

This shift towards renewable fuels in the maritime and aerial transport sectors will give rise to large international market needs for such fuels, again giving rise to a demand for CO_2 and other building blocks for drop-in fuels. Energy consumption for maritime and arial transport in Denmark including both domestic and international transport is expected to demand approx. 1,8 Mt green CO_2 in 2030 and approx. 7,2 Mt green CO_2 in 2050[2].

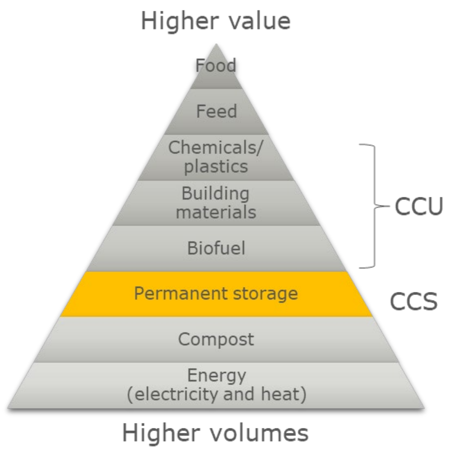


Fig. 4.5: Hierarchy of value of biomass

CO_2will become a scarce resource as the fossil carbon source extraction is minimized, while carbon to produce products such as chemicals and plastics is still needed, and some process emissions of CO_2 are unavoidable. Today approx. 7% of the global fossil oil and gas is used for products, not fuels. This demand is not expected to decrease at the same rate as the need for fossil fuels for power and fuels, but biogenic sources of carbon must meet this demand in combination with carbon harvested by direct air capture. The biogenic carbon will thus have many uses and the value of biomass and biogenic sources for various uses must therefore be considered carefully.

The highest value of biomass resources is human food and animal feed, while the lowest value is the production of heat and electricity or only heat, which should be avoided in the fossil free future (see Fig. 4.5). In between are the uses related to CCU and CCS. In a market-based approach, the balancing of biomass use will self-regulate, but that will require a proper valuation of the climate effect of CCU and CCS.

In order to achieve net negative emissions, which is required according to the IPCC if global warming should not exceed 1.5-2 °C, and in order to compensate fossil carbon use, there is an additional demand for green carbon for storage purposes. In this context it must be noticed that carbon neutrality in 2050 requires that all remaining fossil based emissions of CO2 must be compensated by a corresponding storage of biomass or DAC-based carbon by CCS, soil, biomass or materials storage. Together with the demand for biomass to other CCUS activities this will require significant land areas for biomass production.

4.3 Danish CO_2-balance

During the period from 1990 to 2019 the greenhouse gas emissions have been reduced by 40 %, from 77 Mt/year in 1990 to 47 Mt/year in 2019. These numbers do not include the biogenic CO_2 emission, which accounted for

[2] According to the report "*Potentialet for* CO_2*-fangst i Danmark til den grønne omstilling*", link: https://www.dansk-energi.dk/udgivelser/potentialet-CO2-fangst-danmark-til-groenne-omstilling

additional 17 Mt per year excl. bioethanol and biodiesel[3]. The biogenic CO_2 emissions are primarily due to phasing out of coal and an intensified use of bioresources in the Danish energy sector, which in 2019 amounted to 166 PJ per year excl. bioethanol and biodiesel, and out of this 66 PJ per year was from imported biomass (primarily wood pellets), 17 PJ per year was biogas and 19 PJ per year was from incineration of biodegradable waste.

Considering that the future recycling initiatives will reduce the amount of waste available for waste incineration plants, and that the biogas will be used for purposes where CO_2 point capture is not possible/feasible, for example for maritime or arial transportation, the potential of point source capture of biogenic CO_2 was less than 17 Mt/year in 2019. Moreover, in a global context, it is important to consider the global limitations on how much sustainable biomass the world can produce. The demand for biomass is increasing globally, and according to the Danish Council on Climate Change, the use of bioenergy per person in Denmark is almost three times as high as the global potential for sustainable biomass production per person[4]. At the same time, the use of land for biomass production also needs to be considered in relation to alternative land-use options, for example food production, re- and afforestation and nature/biodiversity. It is therefore important to ensure that the use of biomass in a Danish context considers the global/national limitations, and basically achieves a national balance.

The above considerations suggest that the domestic biomass resources can become a bottleneck in a future net-zero CO_2 emission scenario, thus indicating a need for alternative technologies if carbon supply for green fuels, green materials, storage, etc. should be available in a relevant scale in the future. It is therefore of critical importance that the research and innovation focus is not only on the carbon value chain from biomass combustion over point source CO_2 capture to storage. Rather the focus should be broader and thereby both encompass technologies, which either do not involve biomass combustion as intermediate steps for fuels or utilize the bioresources directly in biorefineries.

5 Technology and development roadmap

Key to achieve optimized, economical, and environmentally sustainable CCUS is the development of technical solutions and regulatory frameworks along the entire value chain.

Five tracks along the value chain will provide the backbone of the roadmap activities:

- biological capture and storage
- chemical capture
- geological storage
- non-fuel utilisation
- cross-cutting SSH track

5.1 Key challenges and gaps

The development of a new sector in an international competitive setting involves a broad number of risks and inflections points. They range from technologies with low TRLs, low SRL-levels for storage, uncertainties related to investment-intensive complicated multi-actor value-chains, the absence of viable business models and uncertainties regarding political regulation (Fig. 5.1). Risk reduction activities should be planned, and will vary and involve small scale experiments, large scale testing, continuous systems-analysis and modelling as well as stakeholder involvement. Risk management must be coordinated, and specific risk analysis results aligned with overall expectations for both mitigation and adjustment. Gradually relying more on green CCUS reduces risk in the sense that a multi-source, multi-technology, and multi-actor scenario allows for a diversified pipeline of innovation.

[3] According to the report "*Klimastatus of -fremskrivning 2021*", link: https://ens.dk/sites/ens.dk/files/Basisfremskrivning/kf21_hovedrapport.pdf
[4] According to the report "*Biomassens betydning for grøn omstilling*", link: https://klimaraadet.dk/da/rapporter/biomassens-betydning-groen-omstilling

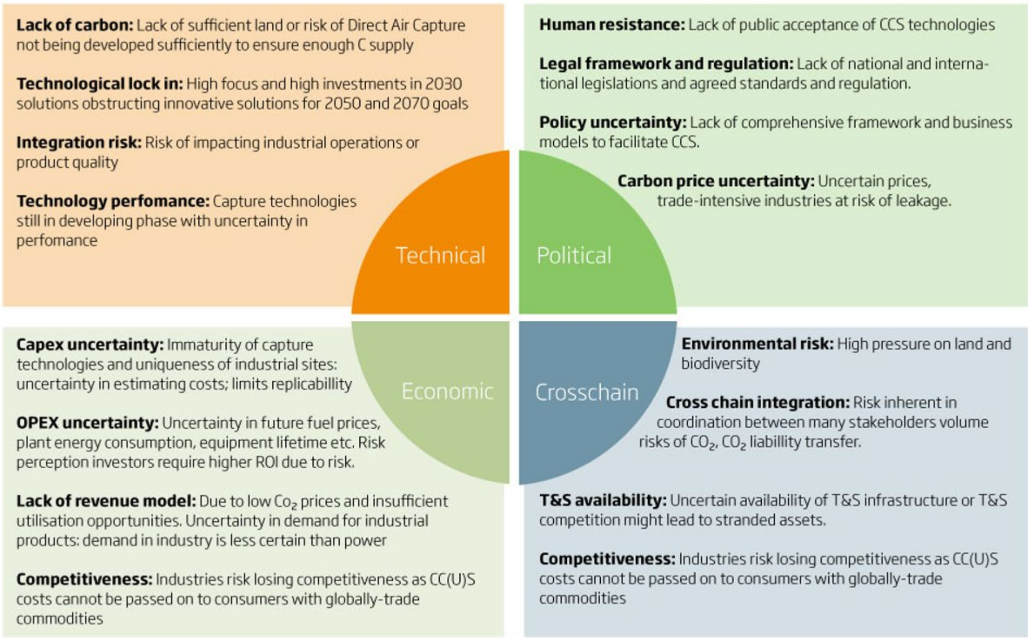


Fig. 5.1: The overall risk factors when developing and implementing CCUS

Besides innovation and development of the capture, storage and use technologies there are a number of sector coupling, regulatory and social science aspects of relevance to the entire transition. The key challenges are:

- the complexity of solutions increases when different value streams are combined and coordinated. Existing sector coupling experiences relate largely to the energy sector. In a fossil free future, the energy market as well as the drivers for carbon flow in society will look much different from today and involve new sectors. Consequently, there is a need to (1) identify new sector coupling demands and potentials, (2) establish regulatory, control and documentation means to facilitate responsibilities and incentives and (3) to agree on long term prices on the exchanged products/resources.
- For sector coupling and smart energy systems to work, reuse of heat and resources must be economically viable.
- The price of electricity needed for hydrogen production or electrochemistry, in relation to CO2 conversion, is too high and must be reduced in order to economically convert CO2 into fuels or chemicals.
- Establishment of regulatory systems with clear rules for accounting and clear rules for counting import/export of CO2 and carbon holding chemicals and materials in the national emissions.
- The Danish government expects a new technology basis to support the emission reduction. There must be a financial structure in place which fertilizes SME or basic technology development allowing for new methods in the market.
- Law and policy which supports an widespread implementation of new CCS and CCU technologies, changed land use patterns and altered consumption patterns internationally.
- Regulation needs must be investigated by addressing relevant externalities arising from current and future CCUS strategies and global standards needs to be developed
- Establishment of a common and cross sectorial value/price and/or tax/credit of carbon, providing incentives for removing/replacing fossil CO_2 and storing CO_2,
- Societal acceptance to CCUS

5.2 Chemical CO2 capture

In Denmark there are several key companies controlling and selling CO2 emission reduction technologies, which can enable an export market already by 2030. There is a need to develop this knowhow, using strategic inflection points, allowing for development, which will sustain a competitive potential also in the future.

Currently CO_2 capture technology in Denmark is developed for small sized CO_2 reduction applications. The largest CO_2 capture technology users are in the order of 50 Kton/year (0.05 Mt/year). As a **short-term goal (2025)** this needs to be scaled up to end-users with a demand of 0.5 up to 2 Mt/year. This calls for innovation, allowing for reduced cost of materials, large-scale process equipment, energy efficiency, optimization of land use and considerations towards industrial integration allowing reuse of heat and cyclic application of resources.

Mainly thermal processes drive the CO_2 capture technology today, but there is a movement towards an increasingly electricity driven society. A complex structure, which uses smart-grid concepts and initializes the basis for flexible operation of the energy infrastructure. As a **mid-term goal (2030)** CO_2 capture needs to fit into this power grid. A clear inflection point will be to develop CO_2 capture technologies, which are purely driven by electricity, going away from traditional high temperature processes.

Current CO_2 capture technologies today runs on dedicated energy supply systems. Other technologies producing excess heat that like Power-to-X and hydrogen production could be couple to CO_2 capture facilities allowing for capture technologies propelled by low-cost waste heat from a variety of sources. A transition phase for the capture technology could include application of very 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.

Technologies must also be developed for Direct Air Capture (DAC). The need for lowering the level of greenhouse gasses in the atmosphere will be urgent in the period towards 2050 and after. Current technologies all require many resources in terms of energy or water supply. Technologies must be developed much further well before 2050, allowing for a **long-term goal (2050)** with an inflection point moving CO_2 capture from high concentration emitters into much lower concentration sources like shopping malls, office buildings, and schools. This will create the technology needed for the positive climate actions in terms of negative CO_2 emission.

Capturing CO_2 for storage or utilisation gives rise to two very different philosophies in the capture process. Focus on cost reduction must therefore be considered based on the end-use application. CO_2 capture on a larger scale has traditionally been performed using solvents. It is likely that this will be the winning technology in the future, but new materials and configurations enabling a significant reduction in energy usage are currently being developed. This must be investigated towards a long-term trend beyond 2050. Not least, biological methods, including enzymes, for CO_2 capture receive increasing interest, as they may be more environmentally benign and less energy consuming.

Some of the current technological challenges around carbon capture are that the preferred amine-based solvents (e.g., MEA) have an energy penalty, are corrosive and release toxic degradation products. Amines are fast at absorbing CO_2 in the scrubber unit but the subsequent release in the stripper requires temperatures up to 120 °C. Solvents with a lower energy requirement in the stripper are kinetically slow in the CO_2 absorber and will, therefore, lead to a bigger footprint of the carbon capture unit. Using biocatalysts in combination with low-enthalpy solvents like carbonate can improve the reaction kinetics dramatically. Further developments within new less tested solvents systems containing biocatalysts are needed as these offer a unique possibility to improve the cost and environmental impact of carbon capture processes.

The cost of carbon capture has significantly come down during the last two decades. The initial applied technologies lead to cost in the order of 80-100 €/ton and all had an energy consumption in the order of 4 GJ per captured ton CO_2. It has recently been seen that the energy consumption reach potential is in the order of 1 GJ/ton and possibly lower, which will give rise to clear cost reduction enabling costs possibly lower than 35 €/ton for CO_2 capture towards 2050.

Capture	Baseline				2025 goal			2030 goal		2050 goal
Finance and SRL	**Subsidiaries**									
		Sector coupling	Investment strategy		Subsidiary system in place					
	Societal readiness level									
	SRL 2	Assessment of current social acceptance and challenges	Involvement of general public	Outreach activities	SRL 6	Environmental study for specific sites		SRL 9		
Implementation	**Thermal driven carbon capture**									
	TRL 9	Brown/Green field feasibility	FEED study	Demonstration	0.5 Mtpa	Large scale heat pumps	Heat integration	4-9 Mtpa	Export & Gigantic scale	5 bn DKK export
	Export and SME creation									
	Low export	Support for SME's	Legal and IP strategy	Business plans	3 SME, export ambition	Seed capital	Sales	10-20 SME, initial export	Overseas customers	Export
	Cost reduction									
	LCA and CAPEX analysis	Alternative building materials	Corrosion tests	10% reduction in CAPEX	Volumetric optimization	Process parameter optimization	20% reduction in CAPEX	Deep sector coupling & flexible operation	<35€/ton	
Innovation										
	Electricity driven carbon capture									
	TRL 4	New solvents	New materials		TRL 6	Solvent optimization	Demonstration	TRL 8	P2X integration	10-20 Mtpa, export
	Biological capture									
	TRL 2-3	End-product analysis	Process optimization	Volumetric efficiency	TRL 6	Demonstration	Upscale & FEED	TRL 8	CCU and Hydrogen integration	1 Mtpa.
	Direct air capture (DAC)									
	TRL 2-3	Solvent loss optimization	New process development		TRL 4	Cost reduction	Demonstration	TRL 7	Cost reduction	<100€/ton

Table 5.1: 2025, 2030 and 2050 capture sub-roadmap goals, which can be back-tracked to project activities.

5.3 CO2 storage and transport

The Danish underground has ample potential for storage of CO2 (see map in Fig 5.2) making it relevant not only to store Danish emissions but also to act as a storage hub for Northern Europe. This could provide opportunities to develop CO2 storage as a mean of creating a new industry with growth and employment in Denmark. The development of large-scale CO2 storage infrastructure in Denmark should be planned with flexible solutions integrated with other sustainable efforts. By planning for large-scale CCUS in Denmark, the unit costs of transportation and storage is more likely to be kept low and thus competitive. Large-scale operation will also attract research and development, which will form the backbone of a future technology export.

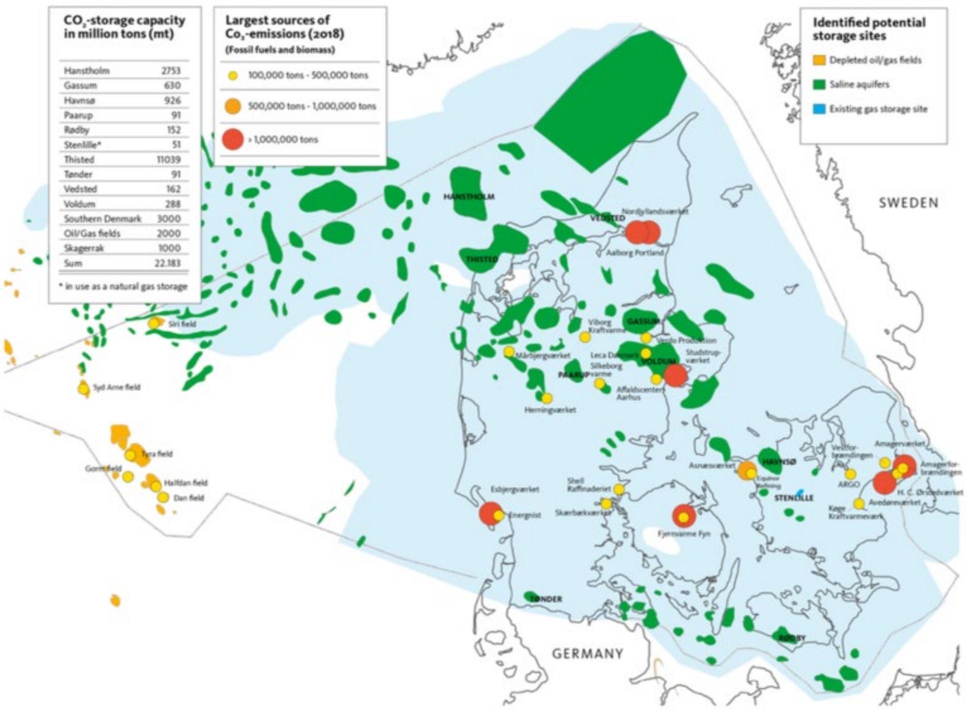


Fig. 5.2: Potential storage sites and main point source emitters in Denmark

Several **storage options** should be examined to ensure that the right solutions are chosen for Denmark. The present roadmap includes perspectives on four different storage options:

1. offshore storage in hydrocarbon depleted sandstone fields
2. offshore storage in hydrocarbon depleted chalk fields
3. offshore storage in saline aquifers, and
4. near-shore and onshore storage in saline aquifers, such as existing gas storage sites.

Each option has its own maturation timeframe and advantages. Offshore storage in depleted oil and gas reservoirs builds on decades of technology development. Furthermore, infrastructure is in place, whereby the surface is connected to the subsurface. By taking advantage of the high initial Technology Readiness Level (TRL), existing infrastructure and reservoir knowledge, this option provides a fast path to CO2 storage in Denmark. Offshore storage in depleted chalk fields has today a lower TRL level than sandstone reservoirs, but chalk is ubiquitous in the Danish underground and this type of reservoir could be developed based on our current knowledge of the reservoir. Offshore storage in saline aquifers in Skagerrak as well as nearshore and on land provides a very large storage potential of several Gt CO2. The location of CO2 storage sites near-shore or on land will aid integration with Power-to-X and other utilities and could thus provide the most optimal storage option in the long term.

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 here can be used to de-risk potential large scale onshore/near-shore storage sites. Because the subsurface is well known from more than 30 years of operations and thorough geological surveys, and due to existing infrastructure, a quick implementation of a test pilot as well as a full-scale demonstration project for CO2 storage could prove possible to fast track a development before 2025. Furthermore, the great experience in public outreach and acceptance of a gas storage site will provide valuable insight in these matters to other potential onshore and near-shore storage sites. Finally, the site has a strategically good location close to large emitters.

Goals at various time frames apply to the development and involves one or more technical inflection points when the goals have been reached notably the transition from pilots to demonstration and to fully operational sites, and from subsidized to full commercial projects. For each goal level a number of **innovation** activities apply relating to alternative (non-liquid) storage, R&D to reduce costs for storage and transport but also testing and qualification of well products for CO2 injection. Quantification of corrosion risks at mixture of water and high CO2 concentration and/or with impurities from the capture process and dynamic flow testing.

- I**nfrastructure** design and planning: Infrastructures for storage sites should be integrated with hydrogen storage and Power-to-X production facilities to take advantage of the large CO2 flow near the storage site to produce green fuels. Therefore, the infrastructure should be planned with a flexibility that considers future needs for CO2 as well as transport and storage of other substances such as hydrogen, green ethanol, methanol and kerosene in-mind and calls for an integration of the offshore wind activities and the infrastructure and data from the North Sea. The national infrastructure should be linked to international infrastructure to allow for import/export of CO2.
- S**hort-term goal** (2025): Focus to enable full scale offshore and onshore demonstration projects totalling 2-3 Mtpa. The demonstration projects will take advantage of access to well-known geology, existing infrastructure and operational knowhow. A national hub strategy must be developed to incorporate all thinkable parts of the infrastructure, including production and transportation of various gases and electricity, energy sources for gas production plants, and energy storage such as hydrogen storage. A financial incentive for transition to private investment are required in the short term. The future investment climate for CO_2 infrastructure and storage must be improved by politically strong and stable signals on carbon tax and storage/utilisation subsidies.
- M**id-term goal** (2030): Focus to provide storage of 8-16 Mtpa by expansion to offshore and near-shore/onshore saline aquifer sites. The mid-term will focus on geological and geophysical characterization of potential sites. The mid-term should also include further development of the infrastructure already in-place so that it can be scaled and with new infrastructure, e.g. pipelines, and ship designs for greater volumes, thus lowering cost through economies of scale, and adapt the value chain for increased collaboration with emerging CCU projects.

- **Long-term goal (**2050): Focus to provide storage of 20-50 Mt/year for Danish sites in total. This gives a potential strategic position to provide storage of imported CO2 from neighbouring countries. Storage sites must be fully integrated with Power-to-X and other utilisation to exploit synergies and coupling to other sectors. Integration with other sectors will enable the Danish industry to take advantage of the CO2 and hydrogen infrastructure.

Storage and Transport	Baseline				2025 goal			2030 goal		2050 goal
	Regulatory framework and business model									
Regulation, business model and SRL	Unclear regulatory framework. Business model not established	Regulatory framework	Business model and market mecha-nisms	Internatio-nalisation	CCS Directive implemented; business models established			Danish transport and storage business model compe-titive in European context		Competitive advantage to Danish process industries and society
	Societal readiness level									
	SRL 2	Assessment of current social acceptance and challenges	Involvement of general public	Outreach activities	SRL 6	Environmental study for specific sites		SRL 9		
Implementation	**Offshore storage - depleted O&G sandstone fields**									
	TRL 5	De-risk for final investment decision	Full scale demonstration project		Provide storage of 1-2 Mtpa	Expansion of storage capacity	Reduce cost based on initial learning	Provide storage of 4-8 Mtpa	Expansion to other sites	
	Offshore storage - depleted O&G chalk fields									
	TRL 3	Mapping of opportunities	Studies of CO2 behaviour in chalk		TRL4	Initiate pilot	Pilot completed	First implementa-tion	Expansion to other sites	
	Offshore storage - saline aquifer									
	TRL 2	Identify 1-3 sites and perform first pass mapping	Geological/lab oratory investigations		Potential mapped	Data acquisition	De-risk for final investment decision	Provide storage of 1-2 Mtpa	Expansion to other sites	Provide storage of 20-50 Mtps for all DK sites. Integrated with PtX/Utility
	Near-shore/onshore storage									
	TRL 2	Seismic and well data acquisition over known structures	Solidify portfolio of national storage potential	Initiate pilot for storage at gas storage site	Near-shore/onshore pilot	Temporary CO2 storage for PtX/Utility	Full scale demonstration project	Provide storage of 2-4 Mtpa. Integrated with PtX/Utility	Expansion to other sites	
	Existing onshore gas storage site									
	TRL5	Final assessment of reservoir and de-risk.	Initiate onsite pilot for storage	Full scale demonstration project	Provide storage of 1 Mtpa	Investigate feasibility for CO2 storage at gas storage site	Expansion of storage capacity	Provide storage of 1-2 Mtpa		
	Infrastructure for transport - ships									
	Existing infra-structure for natural gas	Qualifying existing ships and infra-structure	Develop hub strategy	Adapting ship designs	National infra-structure developed	Connect national and international infra-structure				
	Infrastructure for transport - pipelines									
	Existing infra-structure for natural gas	Mapping options and needs (also for hydrogen and PtX) in international perspective	Technical qualification (engineering and lab tests)	Develop hub strategy	Final strategy for new and existing infra-structure	Development of national infra-structure	Connect national and inter-national infra-structure			
Innovation	**Alternative non-liquid storage (immobilisation)**									
	Initiate investigations in mineral-sation processes	Application of storage in biochar	Storage in high value solid materials		TRL3, sector coupling	Evaluate feasibility of new innovations		TRL8		
	R&D to reduce costs - storage									
	Reservoir rigs, geological knowledge base	Testing and qualification of well products for CO2 injection	Simulations, reaction models and injectivity of CO2 in reservoir and seal.	Optimise operational and monitoring procedures	Provide cost reduction catalogue	Strengthen monitoring strategies and risk assessment tools				
	R&D to reduce costs - transport									
	Pipelines / ships, TRL level initially high				Optimised ship design	Shuttle ships		Zero emission ship		

Table 5.2: 2025, 2030 and 2050 goals that can be backtracked to the actual project activities for the Storage and Transport sub-roadmap

5.4 CO2 utilisation

CO2 utilisation is expected to be a key element in the carbon cycle to reach the net-zero 2050 target. Even though recycling of materials is generally expected to be considerably improved, a continuous feed of carbon-based materials is still necessary. CO2 utilisation leads at the end to emission of the CO2, and should be based on “green” CO_2 wherever possible. Materials, such as paint, medicine and aviation fuel will require carbon from either a non-fossil source or a hard to abate source such as the steel or cement industries.

CO_2 utilisation technologies have been researched for several decades. However, due to lack of economic incentive only a few large-scale projects have taken form. This type of activity is expected to grow in the near future, with the need for Danish partners.

It should be noted, that CO_2 utilisation has applications which will certainly be addressed by other Innomission roadmaps, especially the roadmaps for green fuels and plastics/textiles respectively. This roadmap therefore focuses on other relevant utilisations.

Direct use of CO_2 is a well-known application. CO_2 is used in food products and EOR installations. EOR is expected to decrease due to focus on lower oil production, but direct use of CO_2 as a refrigerant in heat pumps, cement curing agent, in chemical extraction or process chemical for large scale food is expected to grow.

In the scientific literature, numerous studies are on production of methanol (MeOH) from CO_2, since several countries prepare for a future with MeOH as a key component in the carbon loop. Other chemicals, such as dimethyl ether (DME) and formic acid (FA) have also been studied intensively. The two main routes for CO_2 utilisation are thermo-chemical and biological conversion. Both process tracks have advantages, and Denmark has significant knowledge generated within both routes. Thermo-chemical processes generally require elevated temperatures and pressures, which are expected to be subject to economies of scale. Biological processes generally avoid these expenses, however, may instead suffer from lower volumetric efficiency.

Direct utilisation of CO_2 to chemicals via electrolysis has a significant promise and a strong hold in Denmark. CO_2 electrolysis can produce carbon monoxide through two methods: SOEC (Solid Oxide Electrolysis Cell) and heterogeneous catalysis. Alternatively, carbon monoxide, ethylene, ethanol, and methane can be produced using membrane-based electrolysis.

Ongoing Danish research efforts based on biological processes for CO_2 utilisation involve both direct synthesis of relevant products, and pathways over a variety of platform molecules. In addition, CO_2 can be utilized 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.

The CO_2 utilization industry is expected to grow, and Denmark has the potential to become a world leader, exporting knowledge to Europe and abroad. Development of energy technologies has been an international stronghold for Denmark. Through EUDP, Denmark has facilitated several successful CO_2 utilization demonstration projects and significant private funds have been allocated to development of e.g., CO_2-reduzing catalysts. In order to ensure the transition from scientific publications into public companies, strategic funding for high TRL-projects is required.

Enabling a market for CO_2 utilization will potentially transform the value chain for CDR and minimize the need for storage in the long run, towards 2050.

Utilisation	Baseline				2025 goal			2030 goal		2050 goal
Finance and SRL	**Subsidiaries**									
	Societal readiness level									
	SRL 2	Assessment of current social acceptance and challenges	Involvement of general public	Outreach activities	SRL 6	Environmental study for specific sites		SRL 9		
Implementa-tion	**International development**									
	Market extend: low	Bring technologies to DK	International development projects	EU	3 international projects on utilization	International demonstration of projects	Subsidiary system in place	Int. Deployment of technology	Export finalized technologies	Export worth 1 bn DKK
	Start-ups and first movers									
	Low activity	Efficient tech transfer	Seed capital	Lower marked barriers	15-30 Danish Start-ups	Legal support	First long-term contract	5-10 SMEs	Growth support funding	1-2 larger companies
	Catalysis									
	TRL8	Upscaling	FEED		TRL8 demonstration	P2X integration	Smart Grids	Large scale Construction initialized	Up-scaling	5mtpa
Innovation	**Electrolysis conversion**									
	TRL2	Basic development	IPR		Demonstration	Up-scaling	Reactor optimization	TRL8	Investment	TRL9, +100,000 Mtpa
	Direct utilization									
	Existent	New application	Feasibility studies		TRL 4 for new tech	Business cases	Proof-of-concept	Demonstration	Up-scaling	TRL9
	Thermo chemical technologies									
	TRL5	Demonstration	Reactor designs	Heat recovery	TRL 7	Industrial investment		TRL 9	Contract negotiations	International deployment
	Biological technologies									
	TRL2	Proof of concept	New principles		TRL 5	Demonstration		TRL 8	Large scale demo	First large scale facility

Table 5.3: 2025, 2030 and 2050 goals that can be backtracked to the actual project activities for the Utilisation sub-roadmap.

5.5 Biological CO2 capture and storage

Natural biological systems capture CO2 by photosynthesis and storage in biomass and ecosystems is an ongoing natural process already contributing to storage of carbon. 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. Potentials in increasing and strengthening contributions from biomass storage to the 2030 and 2050 targets in Denmark are significant and include both increased C-uptake (additionality) and stabilization of carbon stored in terrestrial and marine eco-systems (permanence).

Danish research and traditions in land and ecosystem management provides a unique basis for improving and increasing carbon storage in biobased systems or materials though targeted management.

Increased carbon storage by additionality in particular in Danish forests and wooded lands can be obtained by afforestation and forest management to improve the productivity of forests requiring development of R&D into increasing biomass growth, C sequestration and C-storage per area in agri- and aquaculture production through species selection, genetics and management, including long-term C storage in biosystems under different growth conditions and future climates.

Further, there is a need to accurately monitor, model and forecast C sequestration and storage in ecosystems, C-recyclability in products and use of biomass products critical to climate accounting and to ensure that intensive biomass use does not compromise biodiversity and other environmental issues and to generally understand societal value of ecosystem services. Finally, significant biomass production requires improved spatial planning for increasing C storage in rewetted lowlands and coastal ecosystem, and improved governance, investment and policy support on biodiversity and ecosystem service restoration

Storing stable carbon in soils by application of biochar has significant potential. Denmark has strong research and innovative companies in this field working to improve the knowledge on biochar stability and application in general. Biochar is ready for experimental pilot testing but need further R&D on the production by pyrolysis, the impact of feedstocks, management options and carbon stability. Also, potential environmental side effects on groundwater and soil fertility need to be addressed as well as legal, regulatory and financial models to make the use of biochar economically viable.

Aquatic and Marine systems have significant potential for carbon storage in sediments as well as in plant and seaweed production, in many cases based on Nature-based solutions (NbS), that will also contribute to the improvement of both freshwater and marine water quality. These solutions include establishing of eelgrass beds, the extractive blue mussel cultivation, establishment of stone reefs or stabilization of muddy-organic reach sediment through sand-capping.

Storage of green carbon in the built environment via would or biobased fibres has a long tradition in Denmark and several companies are established. Increased use of biobased carbon in the building industry requires a change in building culture and improvement in performance of green carbon materials and technical biofibres such as hemp and flax as well as marine bioresources in buildings and infrastructure and improved utilisation of harvested biomass from current areas of land-use for forestry and agriculture and increased utilisation of low-value biomass for green carbon material.

6 Transversal perspectives across the CCUS value chain

6.1 Int. regulatory, financial and business-related framework models

CCUS is a case of installing a new infrastructure system, which may require an inter-sectorial, long-term model for cooperation between public and private stakeholders. Both financial perspectives and business model perspectives are depending on regulatory frameworks determined by the government, which are not clear at the moment. This adds to uncertainty about viable business models and risk of investment. Efforts to reduce uncertainty will have a positive effect on the willingness to invest and cost of capital in this sector.

As of now, the Danish Parliament and Government are preparing a national CCS strategy to be presented in the summer of 2021, and the national strategy on CCU is planned to follow suit in the second half of 2021.

To fully roll out the opportunities for a Danish CCUS industry and the best link between public and private initiatives, investment strategies have to be defined and the uncertainty of investments in R&D and infrastructure have to be significantly reduced. European countries similar to Denmark have presented potential models for the implementation of CCS that may inspire the Danish way to proceed:

Norway
CCS is acknowledged as one of the technologies necessary to reach the national target of 40 % CO2 reduction by 2030. The state supports demonstration of a full and flexible value chain for CCS. This includes transport facilities and oversized storage enabling cost-effective future growth. State aid is recognized as essential to reduce costs, share risk and stimulate CCS innovation. The state effectively pays the establishment of storage and transport infrastructure, while the market is trusted to develop on its own. State funding covers 80 % of storage and transport CAPEX upfront, while OPEX for storage and transport is covered for 10 years. State aid agreements have commercial incentives to develop markets further. The scheme includes a carbon tax of 50 €/ton and ETS of 30 €/ton for offshore oil and gas emissions. The business plan relies heavily on import of CO2 from surrounding countries and could provide a storage solution for Danish CO2 if an export solution is preferred.

The Netherlands
It is still undecided whether CCS will eventually become one of the technologies that will enable The Netherlands to reach its target of 49 % reductions in CO2 emissions by 2030. Through state aid, the government aims to stimulate a competitive international marketplace and thereby set the scene for the most cost-effective technology/technologies to drive emission reductions. The national scheme includes subsidies for CO2 reduction technologies. CCS projects can apply for subsidies. However, only capture of CO2 can be subsidized. Storage and transport providers would need to agree a share of the subsidy with the capture owner. A 2030 carbon tax target of 120-150 €/ton (including ETS) has been announced.

United Kingdom
CCUS is seen as critical for the United Kingdom to reach its targets of 68 % CO2 reduction by 2030, and net-zero emissions by 2050. Four industrial clusters for CCUS have been identified with a total of 1 billion £ invested up to 2025 to support the establishment of two CCUS projects. By 2030, carbon capture of 10 Mtpa should be established. Further, a "user pays" model is in place. Users of the storage and transport infrastructure pay fees calculated on the basis of connection, capacity and volumes. The fees are paid under an economic regulatory regime, which is a framework that controls revenues for operators. Funding is available for exposed risks such as initial build-up of infrastructure during utilisation, timing of connection etc.

Germany
Since 2012 a federal law regulates CCUS in Germany (KSpG), resulting in the ban of CO2 onshore storage sites by the federal states. With limited offshore storage potential and along with the national CO2 reduction goals, Germany will probably become a CO2 export nation. Naturally, this poses an opportunity for Danish storage projects if it is decided to import CO2.

6.2 DK regulatory, financial and business-related framework models

A value-based regulatory framework
One approach would be to leave the decision on whether captured non-fossil CO2 will be stored underground or used in the production of e-fuels or other carbon-based products to the market. However, an efficient market outcome is highly dependent on the establishment of a fit-for-purpose regulatory framework guided by the socio-economic value of each pathway. Most estimates indicate that storage of CO2 will be significantly cheaper than utilisation in the short term when measured per ton of CO2 avoided, hence storage may be the initial application of captured CO2 – also from sustainable sources. However, it is important that the regulatory framework does not hinder the use of sustainable CO2 for utilisation in case there are consumers with a willingness to pay to cover the costs of CCU.

Further, it is important that the application is flexible in the medium- to long-term, i.e., it can be shifted from storage to utilisation when Power-to-X technology reaches the required scale to match the flow of CO2 from carbon capture installations. Hence, it is important to avoid a lock-in effect, where sustainable CO2 can only be stored underground for a long period of time due to e.g. commercial agreements or state aid regulation. It is also crucial that the regulatory framework allows the market to fully reflect the different inherent characteristics of un-abatable fossil CO2 and sustainable CO2. In particular, the role of sustainable CO2 as the only means to produce renewable fuels or create negative emissions through permanent storage – both of which are required to bring climate change to a halt and eventually in reverse – should shape the regulation. In the long run (2050 and beyond) the regulatory framework must facilitate both the fundamental need for carbon utilisation aspects and for the required storage of enough green CO2 to compensate any continued fossil use as well as to create the required negative emissions.

The realization of the CCUS roadmap requires massive investments in research, development, implementation, and fundamental changes in consumption patterns. Presently, the cost of CCS exceeds the cost of emission with approximately 100 €/ton and the cost of CCU exceeds the emission cost with 200-300 €/ton. This leads to a current lack of investment attractiveness and the absence of (private-public) governance frameworks limit the development of economically viable business models for green or non-fossil CCUS. It is therefore paramount to increase the cost of emissions through a CO2 cost mechanism and to reduce the costs of both CCS and CCU technologies. Reductions in energy consumption can be found through classic chemical engineering disciplines such as process optimisation, optimisation of solvent composition, and the use of heat pumps to minimise energy losses. The benefit of economies of scale and learning from initial projects will furthermore provide the necessary cost reduction. In the decades to come, CCUS must become the choice – not only because of the climatic benefit – but also due to the straightforward business case.

Therefore, the green CCUS is critically dependent on political decisions to the establishment of a common and cross sectorial value/price and/or tax/credit of carbon, providing incentives for removing/replacing fossil CO2, storing CO2, and delivering green CO2 for utilization. CO2 taxes have been proposed as the most efficient and fair means of motivating change but require strong measures to avoid leakage. CO2 taxes motivate current actors to implement technologies and at the same time gives incentives to technology development. Also, it is important that the Danish government establishes a fast-track permit process for CO2 storage. Further, that the largest sites are matured immediately as economies of scale will lower the unit cost and allow us to invest in competitive transport infrastructure and storage plants.

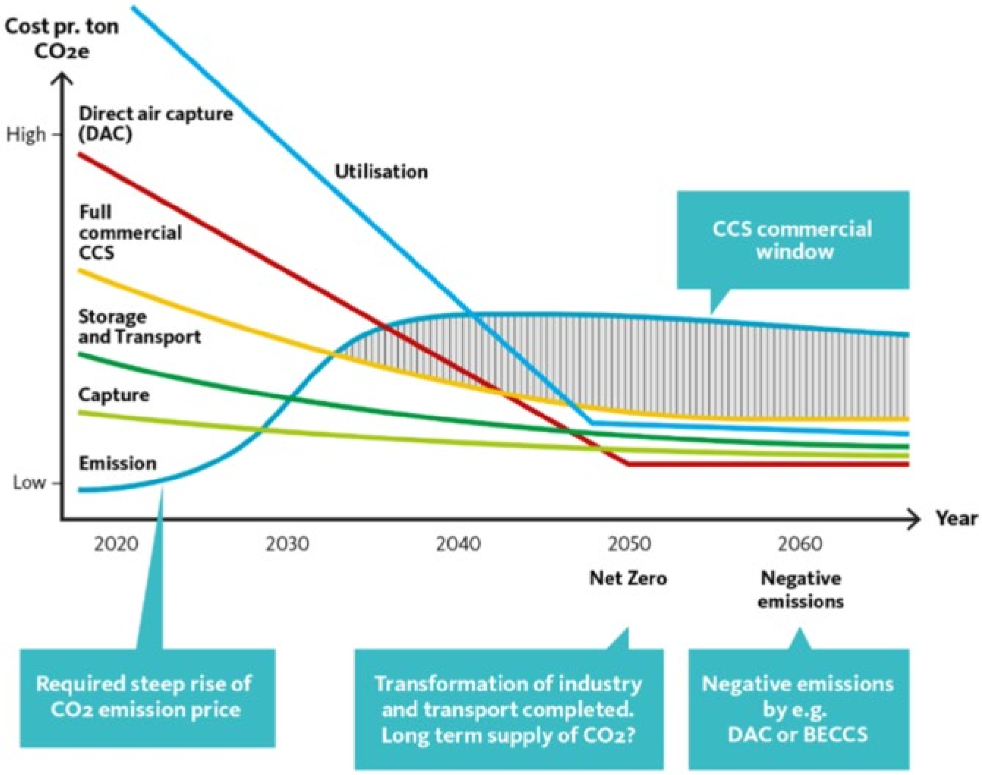


Fig 6.1: Conceptual cost development of critical components in the CCUS Roadmap. Important inflection points occur for each component when commerciality is reached.

Recommendations for regulating capture, storage and use of CO2 (CCUS):

1. Establishment of a stable long-term regulatory framework to create security for investors
2. Establishment of a common and cross sectorial value/price and/or tax/credit of carbon, providing incentives for removing/replacing fossil CO2, storing CO2, and delivering green CO2 for utilization
3. Establishment of a clear framework for pricing of surplus heat for plants with CO2 capture
4. Provide large-scale solutions to drive down infrastructure costs
5. Remove barriers for transport of CO2 (e.g. London convention)
6. Establish legal framework for CO2 storage in Denmark (CCS, Biochar etc.)
7. Allow CCUS subsidy pool from the Danish Climate Agreement to support CO2 capture projects with full flexibility between storage and utilization (e.g. for PtX, biomass) in the project's lifetime
8. Political action to aim at capturing app. 3 MtCO2 per year by the Danish capital region's largest utility companies
9. Establish agreement on fast development of, or access to CO2 storage sites to kick-start the CCUS value chain.
10. Establish incentives and coordination across the value chain through relevant regulation on land management, biomass production, power-, heat- and waste regulation
11. Ensure regulatory means to avoid capturing of CO2 emissions from processes that can be replaced with renewable alternatives in order to avoid that storage of CO2 result in increased use of fossil fuels
12. Climatic effects of fossil and biogenic CO2 must be distinguished – only biogenic CO2 can deliver negative emissions and is a prerequisite for production of renewable fuels via PtX.

6.3 Opportunities and challenges of introducing CCUS in a Danish context

6.3.1 Integration of CCUS into a dynamic energy sector

The energy systems of Denmark and many other countries are undergoing transitions towards more sustainable and renewable sources. This has triggered development of smarter energy systems which will balance supply and demand in more dynamic ways in order to favour more sustainable energy forms over less sustainable. By 2050 the energy system should aim to become almost entirely non-carbon renewably based by 2050 in order to reach societal carbon neutrality. A CCUS system must therefore be an integral part of a smart energy system built on primarily non carbon renewable energy. If designed optimally, new CCS and CCU plants can even become beneficial to the energy sector by functioning as large-scale "regulators", meaning their consumption may be adjusted and thereby assist in balancing the energy system.

6.3.2 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 visualization, optimization, 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 both 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. Solution providers, consultants, and energy supply companies all have significant business potential. Also, 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.

6.3.3 Renewable energy

By developing CCUS as an integral part of the larger energy sector, it will be possible to achieve synergy with the renewable-focused energy system of the future. However, CCUS and Power-to-X are new technologies, which together ultimately are bound to minimum targets of reductions in CO2 emissions, this will require development of new modelling and control methods and algorithms tailored for multi-physics domain processes. The implementation of these new control methods will take a better understanding of optimisation, control and behaviour of large-scale dynamic systems, as well as new innovative energy market constrains, than what is available today.

Although Denmark has already transformed significant parts of its energy supply from fossil-based carbon sources to renewable wind and solar power, carbon-based resources in coals, natural gas and biomass are still heavily used for generating electricity and heating. It is a prerequisite for the green roadmap presented here that the energy sector continues to become progressively decarbonized, such that the Danish carbon budgets become small enough to be covered by predominantly green atmospheric sources. Carbon harvested in biomass or from the atmosphere must in the long-term future (2050) be reserved for chemicals, materials and special fuels, besides, of course, food produced by agriculture and nature/biodiversity.

The energy sector and technology suppliers are preparing for meeting the rapidly changing demands. Relevant partnerships are being formed where industries, consulting companies and research institutes unite to shape the future projects and products. This includes the Copenhagen Carbon Capture Cluster, Energy Cluster Denmark, H2Res, Greenlab Skive etc. These partnerships have ambitions to build the future renewable plants and infrastructure in Denmark, but still there are many technological, regulatory and financial issues to be addressed as highlighted below.

6.3.4 Synergies with Power-to-X, bio-energy and hydrogen

CCUS is a potential supplier of carbon for Power-to-X (electrofuels), in chemicals and in materials (e.g., plastics and fertilisers). Depending on the end goal and concrete components in different types of CCUS plants, the plants can be designed with excess capacities in carbon capture, in the electrolysis unit and/or in the chemical syntheses as well as in combination with different sizes and types of temporary or permanent storage of carbon (Figure 1).

The production of green hydrogen is a prerequisite for providing carbon-based renewable fuels through CCU, and thus a major global focus area. CO_2 provides the carbon source for renewable fuels, while the energy content comes from hydrogen. Denmark has strongholds in this area (ref. Hydrogen Denmark) and furthermore also has sufficient potential wind and solar energy to produce the hydrogen.

Flexibility can also be achieved with hydrogen storage, storage of electricity or biomass in other parts of the energy system. Flexible operation can be achieved in different plant designs, but this requires an understanding of the interaction of these technologies with electrolyses and chemical synthesis. The geographical location of CCUS plants is essential for exploiting some of the industrial and smart energy system synergies. This can be ensured by developing and using GIS platforms focusing on energy infrastructure synergies.

A coherent, energy efficient and integrated smart energy design of CCUS plants can also increase the security of supply, enable the creation of new innovative businesses and jobs.

6.3.5 Integration through modelling

It is critical for the implementation of the roadmap 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, in order 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

The integrated modelling is advanced and will be developed at universities. However, more easily accessible digital tools must be developed already at an early stage of the envisioned partnership to allow stakeholders, as well as policy makers and the public, access to the knowledge that they generate, thereby allowing for insightful decision making and education.

6.3.6 Respecting environment and biodiversity

The roadmap critically depends on the availability of “green” carbon derived from biomass and DAC. Biomass in itself is unlikely to sufficiently deliver all the carbon needed for the roadmap, and therefore 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 for the roadmap will be sustainable and respects our responsibility to protect environmental conditions and biodiversity.

6.4 CCUS cost and investment perspectives

Costs and lack of transparent, commonly agreed and stable market/pricing conditions for CO2 are main barriers for the development and implementation of CCUS projects, and therefor also a main barrier for the needed R&D. The estimated cost of CCUS development for Europe could be up to 50 billion euros and the speed at which CCUS costs can be reduced will be a driver for deployment of large-scale CCUS technologies. The CCUS roadmap relies on a combination of storage and utilization measures (section 4). A recent analysis shows that even if all current available technologies were put to action, c.25% of global GHG emissions would remain non-abatable under current technologies (primarily in seasonal heating, industrial processes, aviation transport and agriculture) (Goldman Sachs[5]) highlighting the importance of "storage" (removals), even in an intensive utilization future.

The CCUS technologies are at very different readiness and cost levels ranging from low-cost natural sinks in forested land (<50 USD/tCO_2) to high-cost technologies such as DACCS (<400 USD/tCO_2) and with significant uncertainty (Fig.s. 6.2 and 6.3). At the same time, they operate at different application scales and potentials meaning that DACCS is likely to become an inflection point for a long-term solution and having a very high potential to capture CO_2 despite the currently higher costs.

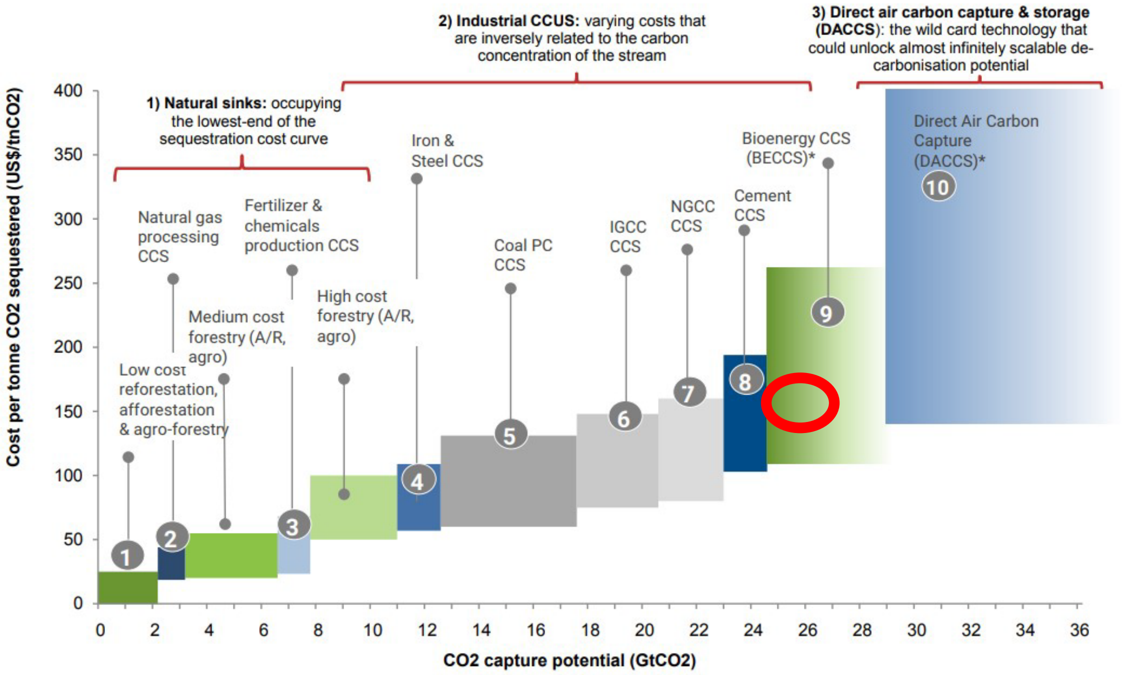


*Fig. 6.2: Carbon sequestration cost curve (US$/tn CO_2 eq) and the GHG emissions abatement potential (GtCO_2 eq). Source: IPCC, Global CCS Institute, Goldmann Sachs Global Investment Research. *DAC technologies still in early (pilot) stage. The read circle indicates that CO_2 capture in cement plants can be less expensive than capture from biomass or coal fired power stations, steel production, etc. See also Fig. 6.3 below.*

[5] https://www.goldmansachs.com/insights/pages/gs-research/carbonomics-green-engine-of-economic-recovery-f/report.pdf

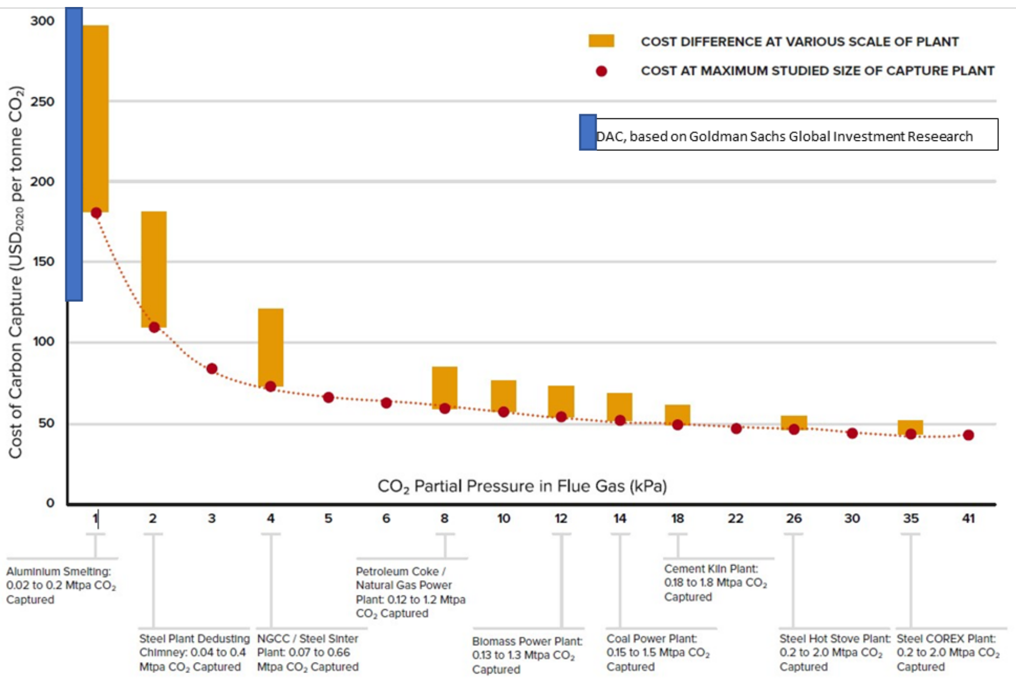


Fig. 6.3. Impact of CO2 partial pressure and scale on the cost of carbon capture. Studied flue gas streams are at atmospheric pressure. The circle marker indicates the cost at the maximum studied size of a single carbon capture plant. Each grey bar indicates the capture cost ranges from 10% to 100% of the scales shown in the callouts for that particular application.

There is a risk of a two-speed de-carbonization process emerging if financial stimulus accelerates the investment in clean tech already at scale (solar, wind, biofuels), while the development of carbon markets and nascent de-carbonization technologies (CCUS, clean hydrogen) may be slowed down or even pushed back (5). This may ultimately delay the technological breakthroughs. Further, massive investments in known technologies or technologies tailored to a short-term solution such as the 2030 goal may become obstacles to investments and development of long-term technologies and solutions. Therefore, de-carbonization may accelerate in the short term, but ultimately delay the long-term path towards net zero. Consequently, governmental legislations and the setting of long term and transparent market regulations such as CO_2 taxes and C/CO_2 valuation mechanisms are essential requirements to facilitate the green transition and development of the markets and long-term investments (Fig. 6.4).

Short-term (- 2025)	Mid to long-term (2025 -)
• Policies and appropriate regulatory framework to ensure transparent investment landscape and cover associated risks. • Mix of fiscal and financial public and private support and investments • Reduced capital cost by intensive R&D efforts in 2. generation CCUS technologies. • Cost reductions by research collaboration and national knowledge sharing. • CfD (Contract for Difference) on CO2 price relative to market CO2 price (e.g. EU ETS) to provide guarantee of revenue. • Market or public reimbursement of industrial CC operational costs • Close international collaboration on regulation and financial instruments.	• International agreed market conditions for CO2 (credits, tax, pricing) enabling investments and operations • Interactions between DK and e.g. the European Innovation Fund securing high up-front capital costs. • Loan guarantees and long-term funding to companies for high-risk projects (close European and Danish collaborative). • Fixed-price funding support providing revenue guaranties. • Public–private risk-sharing model

Fig. 6.4: Financial and regulatory measures for business model elements

7 Social acceptance, communication, engagement of civil society etc.

Discussions about the feasibility and costs of the technology for the end-customer, regulation of the different technologies and especially the lack of societal acceptance regarding on-land-storage of CO2 in several countries (e.g. Germany) have slowed down CCUS implementation. However, a Danish and EU decarbonisation target of full climate neutrality by 2050 is believed to introduce a much stronger momentum, and a willingness to increasingly accept technologies that were previously perceived as controversial – due to the climate crisis urgency and a need for solutions here and now. To enable the deployment of large-scale-solutions, CCUS-technologies are depending on innovative cost models and technology regulations as well as new models of public acceptance. More specifically, it must be demonstrated that the storage of CO2 does not pose a threat to people or the environment, that adequate monitoring takes place, and mitigation measures are available if necessary. Local environmental challenges must be handled in a sufficient and proportional manner. The active involvement of the municipalities and Non-Governmental Organisations (NGO) in Denmark will be key to increase the societal readiness level, and this work must start immediately. Public acceptance is absolutely fundamental to future deployment of a CCUS value chain. This requires managing all relevant stakeholders both from public and private entities to more general audiences. This can be executed by three different tracks:

<u>PR (communication with the public and mass media):</u> Agenda setting, and dissemination of knowledge can be done by ongoing PR efforts. A transparent approach to actively promote public acceptance will be essential to increase the knowledge of CO2, its impact on the climate, and how carbon capture can be an important tool to lower the greenhouse gas effect.
<u>Stakeholder dialogue:</u> An ongoing dialogue with relevant stakeholders and partners is crucial to ensure acceptance and to ensure dissemination of results. Formal partnerships with select stakeholders should be considered.
<u>Acceptance workshops with communities:</u> To promote and sustain the acceptance, stakeholders must engage in a public dialogue with affected communities to address fears and reservations towards the different parts of the CCUS value chain and highlight the benefits of the projects. Given the importance of societal acceptance, the present roadmap does not just target TRL, but also the Societal Readiness Levels (SRL) according to the SRL concept of Innovation Fund Denmark. Right now, the societal readiness level of CCUS can be seen as quite low (SRL 1-3). The proposed roadmap will include research and test cases regarding regulation, cost models and public acceptance. As a first step, these activities should lead to pilot testing in relevant environments. Further, the proposed solutions should be validated locally in cooperation with stakeholders (SRL 4-6) to build the basis for refining solutions and the implementation and dissemination of results (SRL 7-9). In essence, economic research and regulatory research could be the basis for a positive implementation of CCUS in society.

7.1 Educational aspects of CCUS

As a whole new industry develops, it is key to supply high-quality future employees who are able to help build the industry, secure competitiveness, and foster ongoing innovation. Demands for skills on both master and PhD level are expected in this knowledge-based sector. General business administration skills are relevant. Also, green transition management and specialised course packages and full master degrees will have to be developed. These should be built around core aspects like storage technology, geoscience, developing and accessing energy business models, energy systems and network analysis and development, energy infrastructure economics and finance, international energy developments and regulation and energy transition. Social science and business school-based competences will provide a systems-oriented overview and implementation capabilities which supplement technical specialised skills. As CCUS is a sector based on advanced implementation of new technologies in new markets, constant development will be required. Cross-disciplinary educational initiatives between STEM-disciplines and energy economics and business, will further enhance implementation and competitiveness. Entrepreneurial initiatives and focused accelerator programs will help secure academic spin-offs and stimulate business development. Life-Long-Learning and Executive Education initiatives should be initiated quickly to help build change management capacity with a solid understanding of CCUS.

8 Success criteria for the Mission CCUS roadmap

The success criteria are partly outlined by the goals indicated for 2025, 2030, and 2050 in Table 8.1 of the 5 tracks: Biological Capture, Storage, and Utilization. A general success for all 5 tracks is outlined in the table below.

8.1 Technology and implementation roadmap

TRL and SRL are closely related and progression of the two readiness levels will go hand in hand, and will be the precondition for progress and maturation of the CCUS sector. Together with the Danish strongholds and the ability of the partnership, it will be the key elements for the success of this roadmap. Finally, education will become a significant issue and goal for the future. The CCUS development will drive new demands for competences at all levels in the value chain. This is an important priority and precondition for the roadmap. A relevant task for the coming partnership is therefore also a focus on education and entrepreneurship, as lack of competences will result in bottlenecks.

The implementation of the roadmap involves development of several necessary technologies and their integration/interaction supported and facilitated by fundamental and foreseeable societal tasks as economic, legal, and political instruments and in the end also the societal acceptance and consumer behaviour. The range of technologies have different potentials (volume, timeline, sources and scales) and are at different levels of readiness (Fig. 8.1). All technologies are necessary for securing the future fossil free society and involves a mix of decisions and activities from immediate implementation of technologies working at major point sources, the built environment and soils and ecosystems to initiating research and development on low TRL technologies to reach the necessary TRL-levels in time to replace current fossil technologies (Fig. 8.1). Consequently, the implementation involves a cascade of activities applied in close collaboration between all societal actors.

	TRL 1 - 3	TRL 4 - 6	TRL 7 - 9	Rollout
CO_2 CAPTURE (CC)				
CHEMICAL				
Capture from large industry (point source)		2023 (7)	2030 (9)	
Direct Air Capture	2025 (4)	Kiloton scale 2030 (7)	Megaton scale 2050 (9)	
BIOLOGICAL				
Capture from biogas plants		2023 (7)	2026 (9)	
CO_2 STORAGE (CCS)				
GEOLOGICAL				
O&G Sandstone fields (5)		1-2 Mtpa 2025	4-8 Mtpa 2030; 20-50 Mtpa 2050	
O&G Chalk fields (3)		2030	20-50 Mtpa 2050	
Saline aquifer (2)		1-2 Mtpa 2030 (?)	20-50 Mtpa 2050	
Near-onshore storage (2)		2-4 Mtpa 2030	20-50 Mtpa 2050	
Existing onshore gas storage site (5)			1-2 Mtpa 2030; 1-2 Mtpa 2050	
BIOLOGICAL				
Pyrogenic		2025 (5); 2030 (7)	2035 (9)	
Blue carbon ecosystem restoration		2025 (5)	2035 (9)	
BUILT ENVIRONMENT				
• Building with wood and concrete • Asphalt binders & new composites in the build environment, depending on application			2021 (9)	
• Biobased materials, agricultural waste products • Reuse of construction wood, modularity • Industrialization of the building industry • Large buildings		2021 (6)	2035 (9)	
CO_2 UTILIZATION (CCU)				
NON-FUEL				
Microalgae		2025 (7)	2035 (9)	
Lignocellulosic biomass			2030 (9)	
Green biomasses (incl. grass)		2021 (6)	2035 (9)	
Green processes		2030 (7)	Aqueous catalytic 2030 (9)	
	SRL 1 - 3	**SRL 4 - 6**	**SRL 7 - 9**	
SOCIAL SCIENCES & HUMANITIES (SSH)				
SOCIETAL CHALLENGES AND BARRIERS				
Markets, regulatory or legal barriers, subsidies, levies and technical standards (4-6)			2030 (9)	
Citizen involvement and social acceptability (2-3)			2030 (9)	
Cross-cutting technical and energy system challenges		2025 (4-6)	2030 (9)	
Skills and competences		2025 (4-6)	2030 (9)	

Fig. 8.1 - Technology Readiness Levels and milestones for implementation (TRL in parenthesis)

Fig. 8.1 represents the current TRLs for the Roadmap CCUS technologies and expected milestones for the implementation. Technology development and future goals for the roll-out of CCUS technologies will be supported by private and public funding programs dedicated to support the CCUS technology development by 2030 and 2050.

9 Closing Remarks

This CCUS roadmap is the result of the merging of the Appendix 1: Mission CCUS roadmap and Appendix 2: the "Green CCUS roadmap" both submitted to the IFD in the spring of 2021. Both roadmaps provided outlines and significant research demands and solutions within the CCUS domain to support Denmark in reaching the goal of reducing CO2 emissions by 70% in 2030 and becoming CO2 neutral in 2050.

The CCUS roadmap clearly demonstrates how the challenge of developing CCUS to the necessary level of maturity and delivering the necessary contribution combines significant technical challenges with significant societal challenges in the current green transformation with significant implications for land use, environment, biodiversity and societal/human dimensions and it requires clear and strong regulatory and market related means. This highlights the need for clear political strategies and decisions to explore the full and complex potential of CCUS and to facilitate the necessary framework.