Appendix 2: 1112-00010A - The Green CCUS Roadmap - Towards a fossil free future

Roadmaps for mission-driven green research and innovation partnerships (Innomission-roadmaps)

Innomission partnerships: Translating mission roadmaps into sustained actions

The call for mission-driven green research and innovation partnerships is the second phase in Innovation Fund Denmark's (IFD) Innomission program. Phase one generated roadmaps for each of the four missions (https://innovationsfonden.dk/da/programmer/groenne-missioner). Phase two now asks for proposals to form Innomission partnerships to drive action based on the directions outlined in the roadmaps.

During phase one Innovation Fund Denmark received 12 roadmaps within the four mission areas. Of these 12 roadmaps, six roadmaps were selected by the IFD Board of Directors to provide direction to the partnerships in designing action plans. The six roadmaps are described in the call for innomission-partnerships and shown in its full length in these appendices.

Mission CCUS – a roadmap for Carbon Capture, Utilisation and Storage

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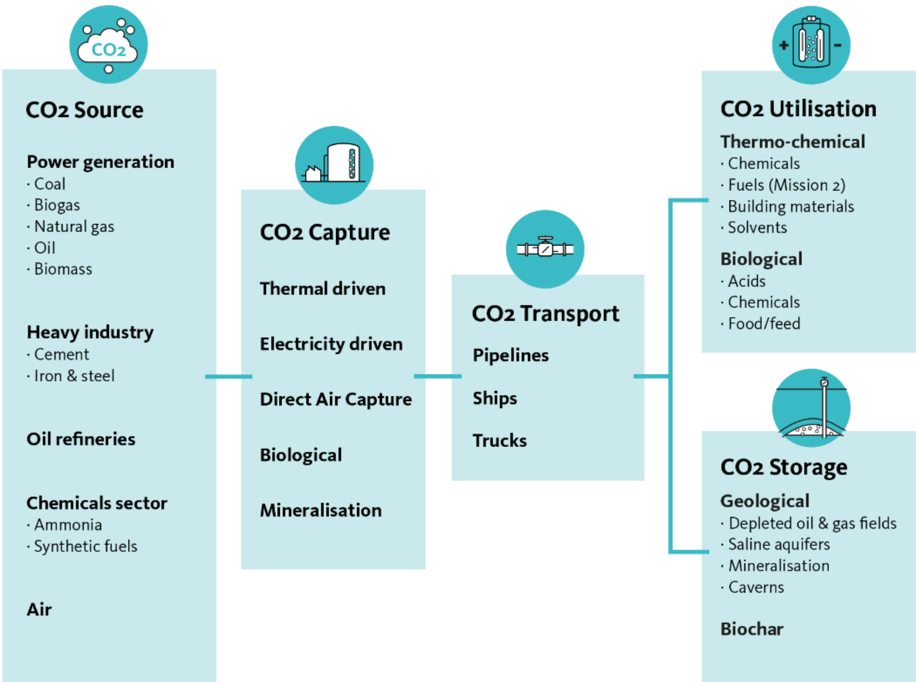
Executive summary

The Danish government has committed to a target of 70 % reduction in greenhouse gas emissions in Denmark by 2030, and net-zero emissions by 2050 from 1990 levels. Carbon Capture Utilisation and Storage (CCUS, Figure 1) is here an important element to achieve these ambitious goals. According to the UN climate panel IPCC and other authoritative bodies, carbon emissions need not only to be minimized but even to become net negative by 2050 to mitigate long term climate effects. Apart from afforestation, only carbon capture from renewable sources with storage may contribute to negative emissions. Thus, calling for negative emissions is effectively the same as calling for millennium scale storage either in the underground, mineralised or as biomass.

Figure 1: The CCUS value chain illustrating key components of capture, transport, utilisation, and storage.



There is an urgency to identify and address the political decisions that will be pivotal for the development of a range of opportunities and business cases within the CCUS value chain in Denmark. A number of pending political and regulatory decisions will have a significant impact on the implementation of CCUS in Denmark.

The main priority for the present roadmap is to set the scene for a significant contribution to the 2030 reduction target of 70% greenhouse gas emissions. In addition, the roadmap describes the potential to build a strong business case based on the Danish geology and technological knowhow. A wide range of CCUS stakeholders in Denmark – researchers, large scale public and private emitters, technology providers – joined forces to produce this roadmap and, more importantly, to align their efforts in a way that will be instrumental for meeting the ambitious goal of CO2 emission reductions.

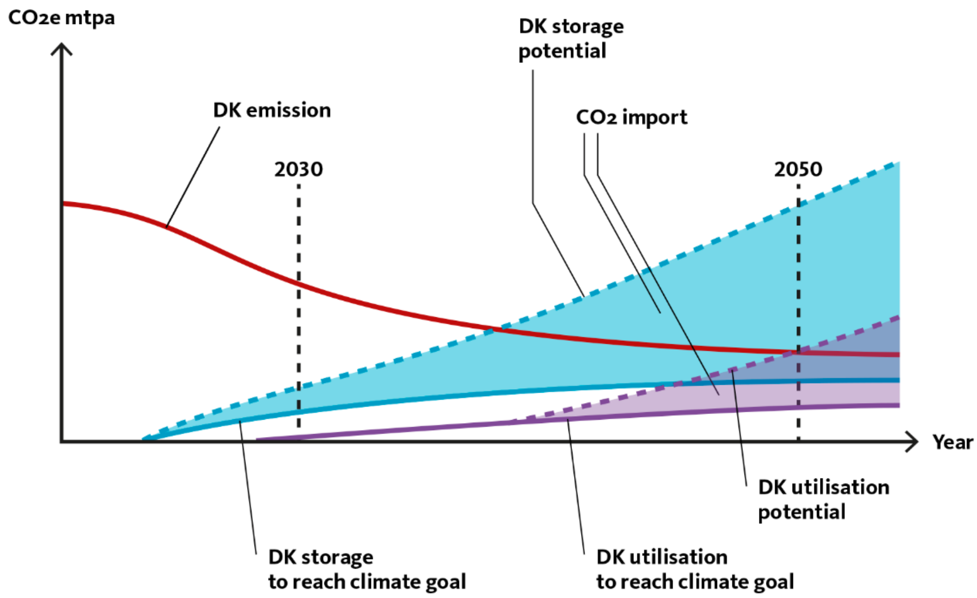
Based on the discussions, and the experience of the involved stakeholders, the roadmap considers a contribution of 4-9 Mtpa (million tonnes per annum) CO2 reduction from CCUS to the 2030 target, as suggested by the Climate Program by the Danish Government, to be realistic. Prerequisites for this are acceleration of the capture technologies, development of national infrastructure for transport, and maturation and de-risking of large potential storage sites.

Once these goals have been reached, it will be possible to increase the CO2 reduction from CCUS considerably in the years beyond 2030.

Carbon Capture and Storage (CCS) is an existing technology. The vast capacity for CO2 storage in the Danish underground provides a potential to serve as more than just contributing to the national CO2 emission reduction targets. If the necessary political support and societal acceptance can be established, Denmark may contribute to solving the reduction challenges of neighbour countries, while at the same time build a considerable business potential. On the long term, Denmark has the potential to provide millennium scale storage of tens of Mtpa CO2, based on own emissions and import (Figure 2).

Carbon Capture and Utilisation (CCU) is still an immature and costly technology, however ongoing research and development will make it gradually more important as a contributor to the 2050 net-zero target. Following the energy transition, captured "green" CO2 will not only be a way to reduce atmospheric levels of CO2, but also the only source of CO2 as a raw material. In addition to the business potential for storage of imported CO2 described above, Denmark has the potential to build a business case on conversion of imported CO2 (Figure 2) into valuable products that can be exported.

Figure 2: Vision of CO2 reductions towards 2050 and beyond.

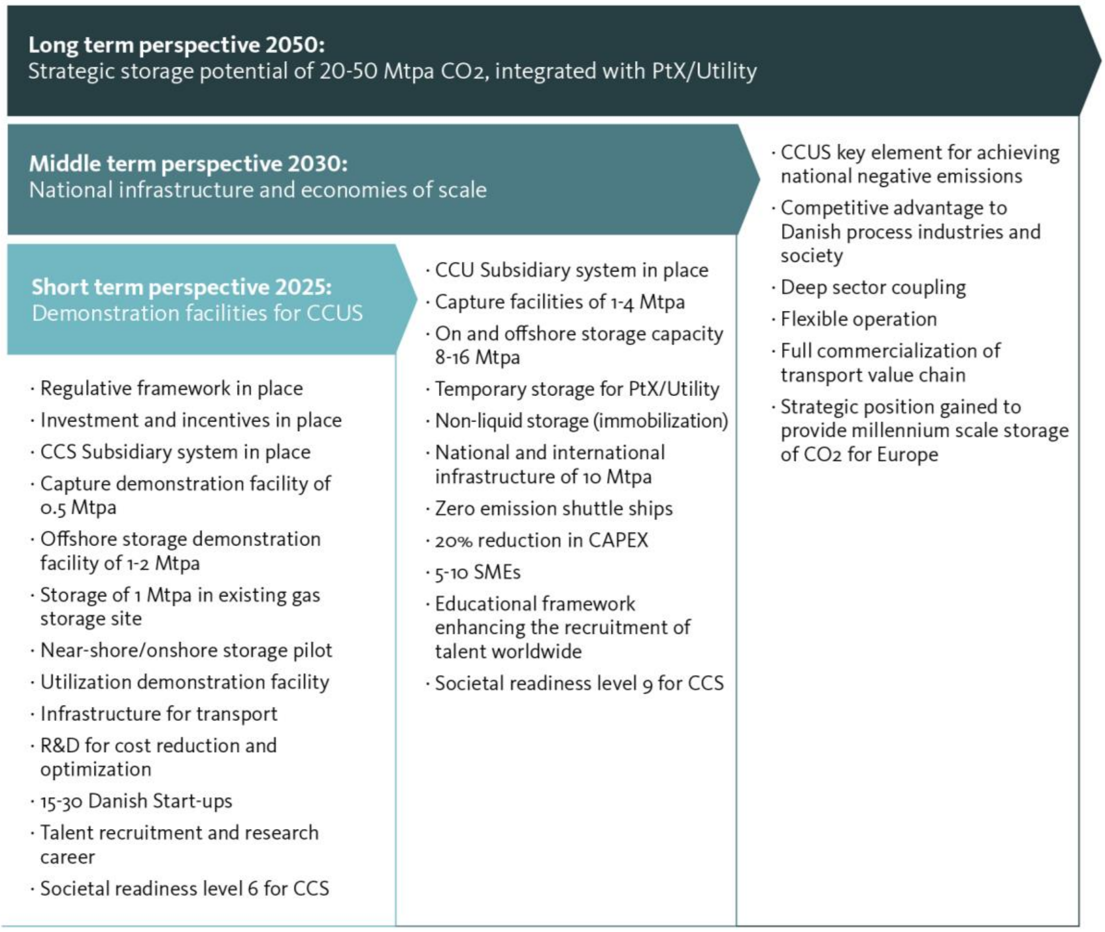


In the short to middle term, 2021-2030, CO2 capture combined with underground storage provides significant emission reduction potential. Studies and demonstration projects are ongoing to optimise and scale capture technologies. Suitable storage sites have been identified on-, near- and offshore Denmark, ranging in maturity from well-known depleted hydrocarbon fields and gas storage sites to less explored structures. Regardless of how much CO2 will be needed for utilisation vs storage in the 2030-2050 horizon, it is crucial to develop and optimise CO2 capture technologies as quickly and environmentally friendly as possible. Also, in this time period, it will be critical to enable negative emission of CO2, meaning a net removal of CO2 from the atmosphere. Currently, CCU products are not considered a carbon removal technology, but rather a CO2 emission delay or recycle technology (carbon neutrality). For large scale removal of CO2 from the atmosphere it seems likely that bioenergy production with capture or direct air capture combined with underground storage is needed. Naturally, the main focus must be on developing new technologies, materials and practices that emit less greenhouse gases, as many of the hard-to-abate point source emitters are already doing. After 2050 a new equilibrium could be reached where the emitted volumes of CO2 can be captured entirely by biological processes.

The main research and development challenges for CCUS will address the need to mature and optimise the technology, integrate it to the industrial and energy system, establish economies of scale, logistics etc., creating a supporting regulatory and commercial framework, establish economies of scale, develop a national infrastructure with international links and finally obtaining a social license for CCUS. The CCUS innovation should not focus exclusively on the resulting CO2 emission reductions. There is also a need to develop a sustainable CCUS system. Fortunately, Denmark has both academic and industrial strongholds when it comes to development of more environmentally benign chemical engineering regimes involving enzyme technology, microbial biotechnology etc.

The present roadmap outlines various potential tracks to achieve the required CO2 emission reductions at the short and long term, and to pave the way for future green CO2 capture. The key goals in the roadmap are summarised in Figure 3.

Figure 3: Key goals and timeline of the roadmap.



Introduction

Organisation of the roadmap process and contributing partners

DTU and GEUS are overall responsible for the coordination of the Mission CCUS roadmap-process. The roadmap document was developed by a Steering Committee representing a significant part of the existing knowledge within CCUS in Denmark. The members of the Steering Committee all have many years of experience in the area from national and international research, development, and demonstration projects. Professor, Head of DTU Chemistry Erling H Stenby and State Geologist, Head of Reservoir Department Maj Wendorff from GEUS headed the committee. A Stakeholder Committee with participants from the broad range of organizations and companies across the value chain has been consulted and many have contributed actively to the developed of Mission CCUS.
The following organisations and companies participated in the Mission CCUS Steering Committee and Stakeholder Committee:

Steering Committee:	Stakeholder committee:	
DTU (Chair)	Copenhagen Business School	Kalundborg Symbiose
GEUS (Co-Chair)	Cowi	Leca Danmark – Saint Gobain
ARC	Danish Shipping	Maersk Drilling
Gas Storage Denmark	Decision Risk Analytics	NIRAS
Haldor Topsøe	DI Energi	Ocean Team
INEOS	DI Proces	Port of Aalborg
Novozymes	Drivkraft Danmark	Port of Hanstholm
Ørsted	Energistyrelsen	Rambøll
Pentair Union Engineering	Energy Cluster Denmark	REintegrate
TOTAL	Equinor Danmark	Renew Energy
Wintershall Dea	Eurofins	Semco Maritime
Aalborg Portland	Evergas	Teknologisk Institut
	FL Smidth	Thisted Kommune
	Force Technology	University of Aarhus
	GEO	University of Copenhagen
	Green Hub Denmark – Aalborg Kommune	University of Southern Denmark
	GreenLab Skive	WellPerform
	Greenpeace	Welltec
	HOFOR	Aalborg University
	Hydrogen Valley	

Links to other Innomission roadmaps

CCUS is the topic of one of four Innomissions. CCUS and will not operate in isolation but will have several interdependencies in relation to the other three Innomissions. This is most evident for Innomission 2, "Green fuels for transport and industry (Power-to-X, etc.)", since this is the future utilisation of CO2 with the largest potential. CO2 could become an important raw material for the production of various green fuels. Therefore, carbon capture should be developed in a way that over time secures the necessary supply for the relevant production technologies outlined by Innomission 2.

Similarly, CO2 is a possible raw material for production of plastics and textiles, which are covered by Innomission 4. And finally, Innomission 3, on "Climate- and environment-friendly agriculture and food production", will also have some interdependency with CCUS, as agriculture and food production are important elements of the carbon cycle and because storage of CO2 as biomass provides a positive feedback loop.

In this roadmap, we will focus on the use of CO2 for chemicals and materials.

Strongholds: State-of-the-art and beyond

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 and Direct Air Capture (DAC), to pure biological methods such as large-scale afforestation. The first step of CCUS is capture of the CO2, but the removal does not occur until the CO2 is stored in the soil, is permanently stored as a solid material, or as a dense fluid in the subsurface.

CO2 capture is applied on a large scale in fossil industry to produce CO2 emission free electricity or natural gas. This includes a limited amount 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. The application of carbon dioxide removal using carbon capture on air (DAC) or Bio Energy systems (BECCS) is currently being explored. This is a new trend compared to the known carbon capture from large industrial point sources (CCS) but no large-scale DAC or BECCS systems have yet been established.

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.

The annual use of CO2 is in the order of 2-300 Mtpa 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.

The national position of CCUS

The Danish government has committed to a target of 70 % reduction in greenhouse gas emissions in Denmark by 2030, and net-zero emissions by 2050. CCUS is seen as a critical element to achieve these ambitious goals. The total greenhouse gas emissions for Denmark in 2019 were 46.7 Mtpa CO2-equivalents. This number includes uptake/emissions from soil and forests (so-called LULUCF). This amount represents a 40 % reduction in Danish greenhouse gas emissions from 1990, which is recognized at the international baseline year for greenhouse gas emissions.

According to projections from the Danish Energy Agency, current policy measures will lead to further reductions in emissions resulting in a total emission of 35.0 Mtpa CO2-equivalents in 2030. This represents a 55 % reduction from the 1990 level. In other words, the current projection will leave a deficit of 15 % points in meeting the Danish target of a 70 % reduction in 2030. To achieve the 70 % target, a further reduction of 11.8 Mtpa CO2-equivalents will thus be needed.

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 Mtpa in 2025 and 0.9 Mtpa 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.

National strongholds

Capture
Denmark has highly competitive companies working on small- and medium-scale solvent-based carbon capture systems. Danish academic research is internationally recognised and respected, with participation in many EU projects. Many activities have been initiated with financial support from DFF and EUDP.

Utilisation
The market for CO2 utilisation so far only has a few players in operation. However, it should be noted that research and development within utilisation is thriving in academia and industry. A wealth of projects involving conventional production designs with captured CO2 as a raw material, as well as biological production designs, are ongoing. Public research programs have supported many types of projects. Not least, the production of methanol has received significant attention.

Storage
Operational knowledge and site-specific knowledge of the subsurface is available in Denmark from offshore oil and gas fields and onshore gas storage sites. Vast amounts of subsurface data have been acquired over decades giving deep technical understanding of the geological structures and reservoirs. National and international research programs have supported several academic research projects. The Danish CO2 storage potential has been mapped by GEUS, which also hosts a national database with subsurface knowledge.

Transport and infrastructure
Through Denmark's rich maritime history and position as a world leading maritime nation, Danish shipping companies have decades of knowledge and experience with development and operation of safe and efficient transport of liquified gases. An existing national gas transmission system leads natural gas from the North Sea to the distribution networks on land. The transmission system in Denmark is route to Germany and Sweden, and to the two Danish gas storage facilities.

International strongholds

Currently, export of CCUS technologies is limited. However, several Danish academic and industrial partners contribute to European and other international large-scale research, development and demonstration projects.

Strongholds to be strengthened and developed

Capture
Danish SMEs and at least one big, international company with strong presence in Denmark are strongholds, with potential for further development. To lower the risk for SMEs, large-scale demonstration projects could support this development.

Utilisation
Several Danish companies and universities have in-depth knowledge regarding utilisation technologies and industrial solutions are already available. To exploit this knowledge a local market must be in place. Together this will create the basis for further innovative start-ups. Here, significant seed capital is necessary to lower the market barriers. For the less mature bio-based utilization Denmark has several industrial and academic strongholds that could develop and mature this area over the coming decades.

Storage
In-depth knowledge on storage technologies and processes - including experimental setups at relevant high pressures and temperatures – exist at several Danish industries, institutions and universities. This includes geology and geophysics, drilling, well technology, as well as reservoir and process engineering. Expertise from the oil and gas area can quickly be transferred to CO2 storage.

Transport and infrastructure
Risk-sharing and funding initiatives are needed to support the investment in highly specialised assets for CCUS-related transport. This would strengthen the position of Danish Shipping (Det Blå Danmark) further as an industry leader within transport for CCUS.

Within all four areas additional research and researcher education is needed to meet the demand for innovation and experts during the implementation and expansion of the CCUS industries.

Technology and development roadmap

Key challenges, gaps and inflection points

Key challenges to the development of CCUS are:

- A legal basis assuring that CO2 can be stored in the Danish underground (onshore, nearshore, offshore).
- A legal basis assuring that CO2 can be transported across borders (London Convention) for the purpose of storage or use.
- The cost of capture-transport-storage versus the price of emission. The present cost of capture, transportation, storage by far exceeds the price of emission. It is expected to change due to upscaling, further research in, and maturation of the required technologies in combination with subsidies until the market price of CO2 emission reaches a higher level.
- The CO2 capture technology for large scale application relies on solvent based principles. Several technologies must go through up-scaling engineering for implementation on large scale, to reduce cost on capture.
- CO2 conversion needs significant electricity and investment cost for highly technical installation. Fundamental research is needed to bring down the cost of CO2 conversion.
- The cost of utilisation exceeds the price of emission. Hence more research and innovation are needed to optimize existing technologies as well as support for start-up companies within new technologies.
- A holistic view on the whole value chain is needed; carbon capture and transportation are prerequisite for carbon storage and vice versa. Links in the value chain can break, e.g., if a large supplier of CO2 closes or changes to a non-emitting energy source. A backup network within the value chain is therefore needed. An adequate infrastructure is important to guarantee supply and offtake of CO2.
- Political decisions like CO2 taxes are subject to changes, and this gives rise to a regulatory risk. Therefore, a de-risking of the business model is needed.
- Maturation and qualification of a storage site requires large investments in data acquisition to decrease the risks of an investment decision. Existing low resolution geological data suggest several potential storage sites but acquisition of new seismic and well data for near- and onshore areas is required to improve interpretations of the subsurface, reduce uncertainty and ensure safe operations.
- The current evaluation of the storage containment follows ISO standards. Further research is needed to develop tools for risk management, possibly justifying that simpler assessments can be used.
- A lack of acceptance in the civil society might be a showstopper for CO2 storage for some locations, and work must be done to identify and map out the societal readiness level. Targeted efforts should be initiated to increase the societal readiness level by engaging municipalities and providing information, education and dialogue.
- As Danish oil and gas fields are aging and soon entering the abandonment phase, an opportunity to convert and utilize infrastructure for CO2 storage must be considered before abandonment. Hence, it is paramount that a process for converting existing offshore production licenses to CO2 storage licenses is put in place.

Gaps

- The present regulation in Denmark does not allow for CO2 storage. While it is allowed to inject CO2 for enhanced oil recovery, actions are needed to ensure the regulatory framework for injection of CO2 for storage in Denmark. This should also include the potential for storage of green CO2 to reach a negative emissions strategy.
- 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.
- How will imported or exported CO2 be counted in the national emissions. Likewise, if green chemicals, based on utilized CO2, are crossing country boundaries, regulatory structures must be in place.
- For sector coupling and smart energy systems to work reuse of heat and resources must be economically viable.
- Upscaling of technologies, such as BECCS and DAC, must be supported in order to reach commercial maturity.

- 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.
- The technologies which are available today allow for removal of CO2. To combat climate change technologies, which can remove other greenhouse gases, like methane and nitrous oxide, have to be developed.

Identified inflection points

- When the price of CO2 emission exceeds the cost of capture, transport, and storage. This point marks the shift from subsidized to full commercial market.
- When subsidies of Storage are no longer needed. This point marks the transition to a full commercial international storage market. For this to happen large storage sites should be developed and a transport infrastructure to be in place for economy of scale to work. This should happen in good time before 2030.
- When the price of Utilisation of CO2 no longer exceeds the price of storage. This marks the time when CO2 becomes a commercial resource. This likely happens after 2030 but well before 2050.
- When CO2 capture technologies are no longer based on thermally driven processes but are purely driven by electricity or biology.
- When CO2 capture is not only from high concentration, point source emitters but also form low concentration gas sources like shopping malls, office buildings, and schools. This is expected to happen around 2040 but well before 2050.
- When the CO2 storage capacity exceeds national need for storage. This marks when a CO2 import business is possible. This could happen between 2025-2030.

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 CO2 capture technology in Denmark is developed for small sized CO2 reduction applications. The largest CO2 capture technology users are in the order of 50 kton per year (0.05 Mtpa). As a **short-term goal (2025)** this needs to be scaled up to end-users with a demand of 0.5 up to 2 Mtpa. 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 CO2 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)** CO2 capture needs to fit into this power grid. A clear inflection point will be to develop CO2 capture technologies, which are purely driven by electricity, going away from traditional high temperature processes.

Current CO2 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 CO2 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 CO2 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 CO2 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 CO2 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 CO2 emission.

Capturing CO2 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. CO2 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 CO2 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 CO2 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 CO2 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 CO2. 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 CO2 capture towards 2050.

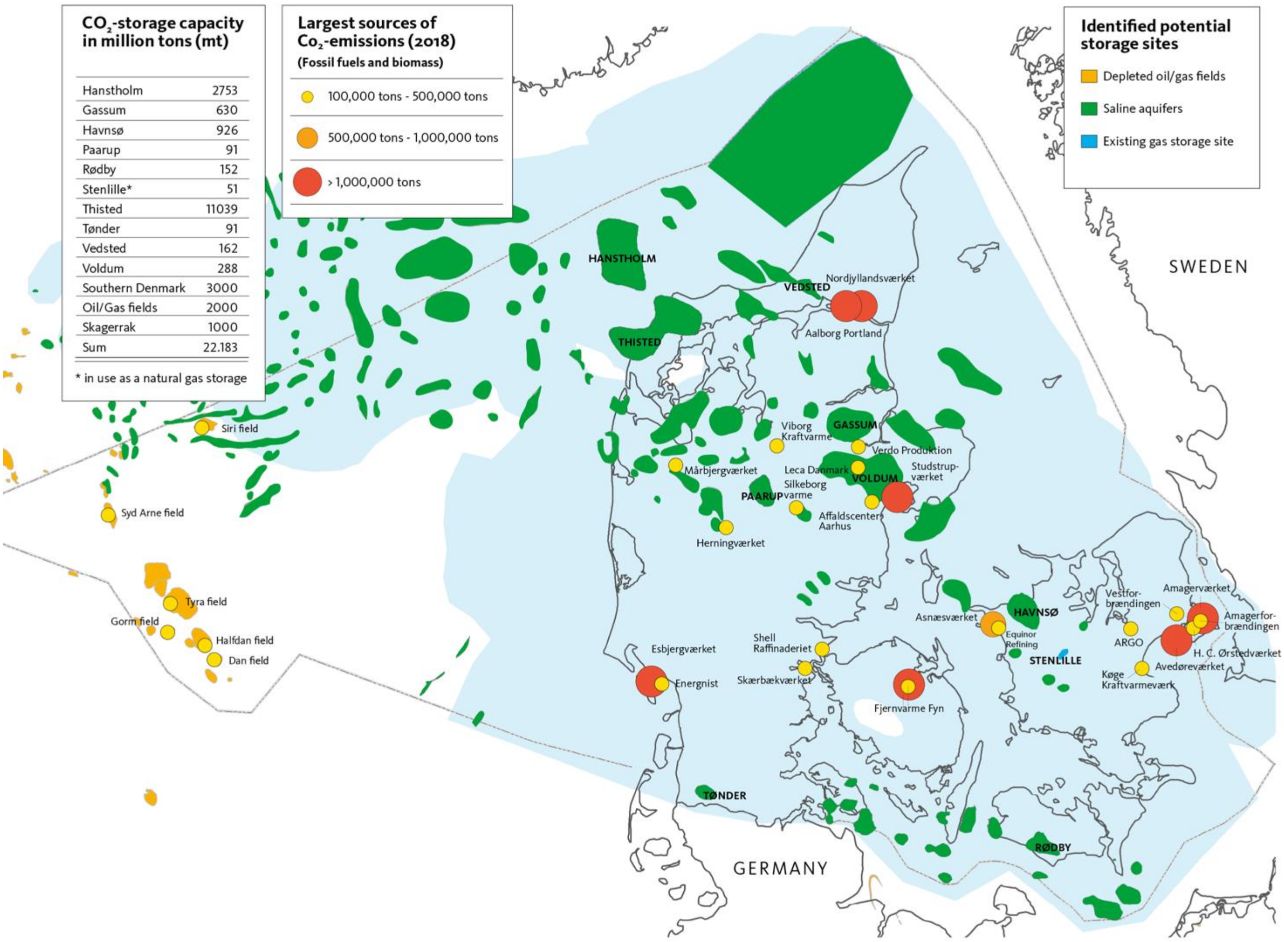
Table 1: 2025, 2030 and 2050 capture sub-roadmap goals, that can be back-tracked to project activities.

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

CO2 storage and transport

The Danish underground has ample potential for storage of CO2 (see map in Figure 4) 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.

Figure 4: 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.

One or more technical inflection points will arise, when the goals described below have been reached notably the transition from pilots to demonstration and to fully operational sites, and from subsidized to full commercial projects.

The design of **infrastructure** 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.

The primary **short-term goal** (2025) is 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.

The **mid-term goal** (2030) is 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.

A potential **long-term goal (**2050) is to provide storage of 20-50 Mtpa 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.

The **innovation** sub-roadmap relates 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.

Table 2: 2025, 2030 and 2050 goals that can be backtracked to the actual project activities for the Storage and Transport sub-roadmap.

Storage and Transport	Baseline				2025 goal			2030 goal		2050 goal
Regulation, business model and SRL	**Regulatory framework and business model**									
	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	Provide storage of 20-50 Mtps for all DK sites. Integrated with PtX/Utility
	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	
	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 minerali-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		

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. These 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.

CO2 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 CO2 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 CO2 is a well-known application. CO2 is used in food products and EOR installations. EOR is expected to decrease due to focus on lower oil production, but direct use of CO2 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 CO2, 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 CO2 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 CO2 to chemicals via electrolysis has a significant promise and a strong hold in Denmark. CO2 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 CO2 utilisation involve both direct synthesis of relevant products, and pathways over a variety of platform molecules. In addition, CO2 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 CO2, which can be integrated for further chemical production.

The CO2 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 CO2 utilization demonstration projects and significant private funds have been allocated to development of e.g., CO2-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 CO2 utilization will potentially transform the value chain for CDR and minimize the need for storage in the long run, towards 2050.

Table 3: 2025, 2030 and 2050 goals that can be backtracked to the actual project activities for the Utilisation sub-roadmap.

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

Transversal perspectives across the CCUS value chain

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 CO_2 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 CO_2 reduction technologies. CCS projects can apply for subsidies. However, only capture of CO_2 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 % CO_2 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 CO_2 onshore storage sites by the federal states. With limited offshore storage potential and along with the national CO_2 reduction goals, Germany will probably become a CO_2 export nation. Naturally, this poses an opportunity for Danish storage projects if it is decided to import CO_2.

Opportunities and challenges of introducing CCUS in a Danish context

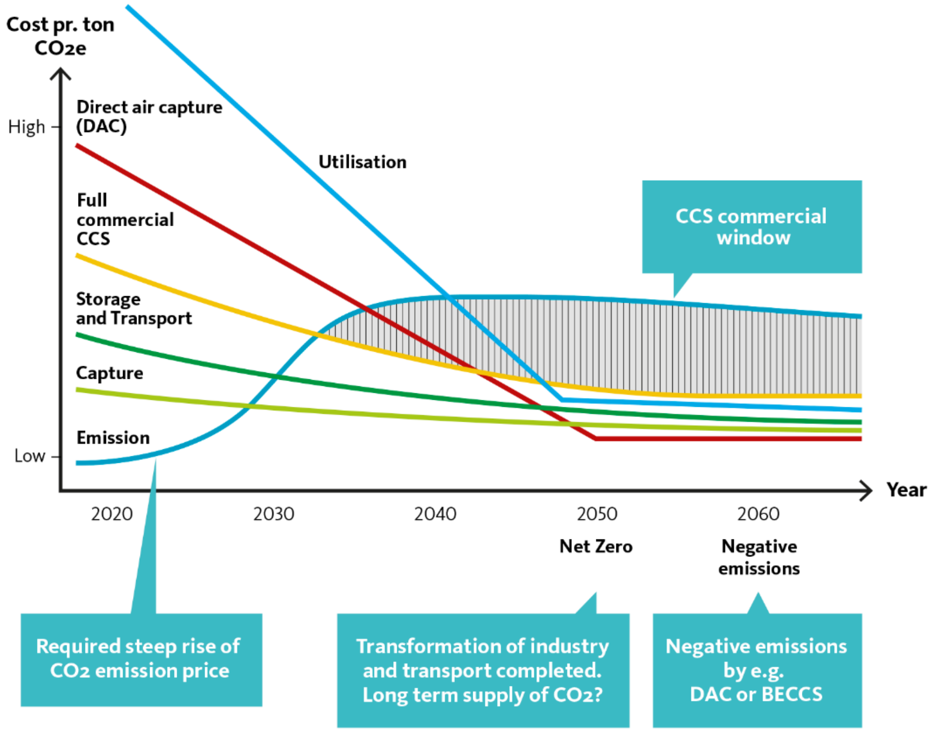
A value-based regulatory framework
One approach would be to leave the decision on whether captured CO_2 will be stored underground or used in the production of e-fuels or other carbon-based products to the market. However, an efficient market outcome is highly dependent on the establishment of a fit-for-purpose regulatory framework guided by the socio-economic value of each pathway. Most estimates indicate that storage of CO_2 will be significantly cheaper than utilisation in the short term when measured per ton of CO_2 avoided, hence storage may be the initial application of captured CO_2 – also from sustainable sources. However, it is important that the regulatory framework does not hinder the use of sustainable CO_2 for utilisation in case there are consumers with a willingness to pay to cover the costs of CCU.

Similarly, 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 CO_2 from carbon capture installations. Hence, it is important to avoid a lock-in effect, where sustainable CO_2 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 CO_2 and sustainable CO_2. In particular, the role of sustainable CO_2 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.

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. It is therefore paramount to reduce the costs of both 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 should be the choice – not only because of the climatic benefit – but also due to the straightforward business case.

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.

Figure 5: Conceptual cost development of critical components in the CCUS Roadmap. Important inflection points occur for each component when commerciality is reached.



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.

A CCUS system needs to be an integral part of a smart energy system built on 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.

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, since CCUS and Power-to-X are new technologies, 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.

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).

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.

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

1. The Danish capital region's largest utility companies are aiming at capturing app. 3 million ton of CO2 per year – but it requires immediate political action
2. A stable long-term regulatory framework is necessary to create security for investors
3. There is a need for an agreement on development of, or access to, one or more CO2 storage sites as soon as possible in order to kick-start the CCUS value chain. In the short term, the Danish state must allocate the necessary funds for GEUS to investigate if various Danish geological formations are suitable for storage of CO2
4. The CCUS subsidy pool from the Danish Climate Agreement should be used to support CO2 capture projects with full flexibility between storage and utilization (e.g. for PtX) in the project's lifetime
5. There is a need for simultaneous development of the entire CCUS value chain. This imposes a need to create incentives across the value chain, as well as coordination of relevant regulation on power-, heat- and waste regulation
6. Establishment of a clear framework for pricing of surplus heat for plants with CO2 capture
7. Need for large-scale solutions to drive down infrastructure costs – CO2 clusters such as C4 are clearly obvious in this regard
8. It is necessary to ensure that barriers for transport of CO2 are removed (e.g. London convention) and that storage of CO2 is legal in Denmark
9. CO2 emissions from processes that can be replaced with renewable alternatives should not be captured. Storage of CO2 must not result in increased use of fossil fuels
10. There is a need to distinguish between the climatic effect of fossil and biogenic CO2 – only biogenic CO2 can deliver negative emissions and is a prerequisite for production of renewable fuels via PtX.

Specific issues relating to large-scale industry emitters

Industry stakeholders with large CO2 emissions call for further research and development regarding heat demand in carbon capture plants, heat integration, local conditioning, storage and shipping facilities, transport systems for CO2, permanent underground storage, pilot testing, and regulatory framework. As for heat demand in CO2 capture, process optimisation is needed to reduce the steam demand and steam quality requirements in the carbon capture plant and in heat integration, utilisation of waste heat including high-temperature heat pumps, compression heat regeneration etc. is essential when introducing carbon capture on a heat and power plant. Local facilities for conditioning, storage and shipping are a substantial but often overlooked element of CCUS costs. Optimisations and cost reductions are needed here. The same can be said for pipeline systems and ship transport systems. Reliable and low-cost options for permanent underground storage (in Denmark or elsewhere) needs investigations and development. Investigations into Danish storage options should start very soon in order for storages to be available in 2025 and prolific before 2030. Further, some large-scale industry emitters see CCUS costs as the main hindrance for widespread implementation. For example, a full-chain abatement cost of 175 €/ton CO2 would increase the prices of cement with 100-150 %. Another hindrance is the lack of framework conditions, which are needed to build a viable business case. This includes lack of CO2 infrastructure, limitations in the present function of the EU Emission Trading System, understanding of who will get the CO2 benefit from CCU/Power-to-X solutions, and availability of financing or state subsidies.

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:

PR (communication with the public and mass media): 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.

Stakeholder dialogue: 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.

Acceptance workshops with communities: 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.

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.

Implementation roadmap

The below passages describe the proposed set up of governance, finance and activities in a partnership for Mission CCUS.

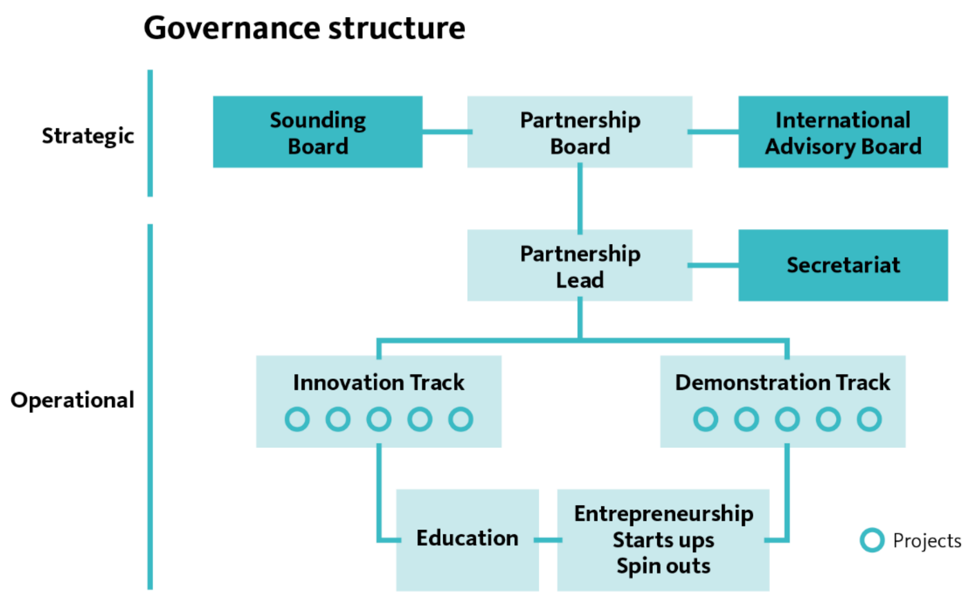
Governance model

We suggest a partnership model for implementation with defined roles and responsibilities and members who are committed to all 5 years of the project. One institution will host the programme and thus be responsible for necessary administrative tasks (at secretariat level) and hiring of Programme Lead. The advantages of this model are e.g. that partners and commitments are known upfront and that the programme will have an easy take-off as necessary support functions are in place with host.

Envisaged bodies and roles

- **Partnership Board:** Responsible for vision, policy and strategy of partnership, including selection of projects, stop-go decision of projects and educational aspects. Appoints and oversees management, monitor performance of the organisation, strategically identifies and manages risk. Includes representatives from all members. Responsible to Innovation Fund Denmark.
- **International Advisory Board:** Advises Partnership Board on vision, policy and strategy. Special scientific members advise Programme Lead on scientific and innovation issues.
- **Sounding Board:** Advises on public awareness and acceptance, environmental concerns and local matters.
- **Partnership Lead:** Responsible for implementing the programme in collaboration with track leaders; develops and deliver on policy and strategy; responsible for management of project portfolio, in charge of secretariat and support of governance processes, measures performance.
- **Secretariat**: Responsible for legal, finance, communication, reporting, day-to-day administrative operations, etc. of entire programme.
- **Track Lead:** Responsible for implementing the sub-programme i.e. management of project portfolio.

Figure 6: Governance model for a Mission CCUS Partnership.

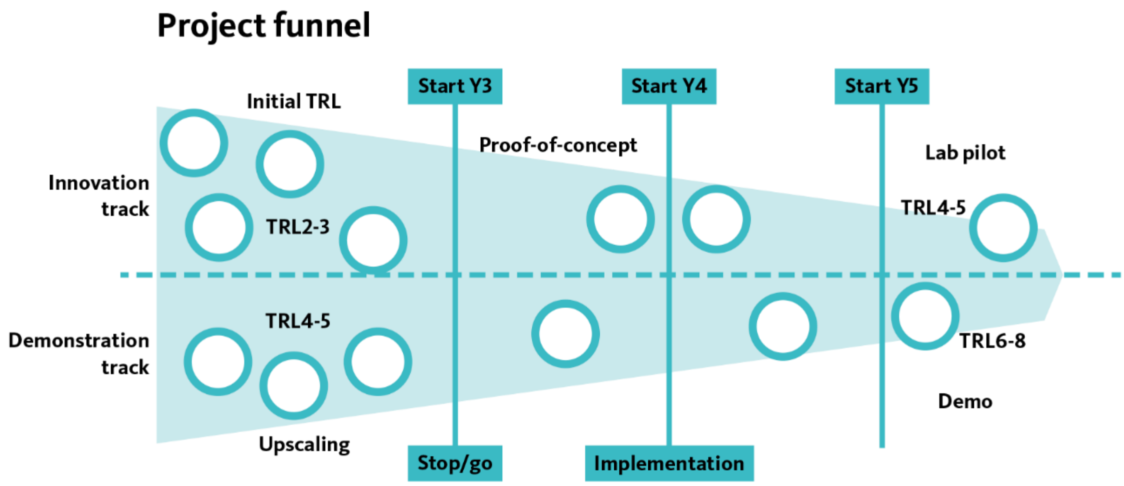


Innovation model

As the CCUS Innomission partnership(s) will run for only five years, it is unrealistic to expect a TRL lift, at this scale of innovation, from TRL 2 to 8. Furthermore, there is an urgent need to reach a very high TRL already by 2025. This calls for a two-track model for the project portfolio and technology maturation:

a. **Innovation track**: will initialise a development path with a starting point of TRL 2-3, where technologies have reached basic principle design in the lab in a narrow and controlled environment. Projects in this track are expected to reach TRL 4-5, i.e. a minimum of proof-of-concept, during year 2 to 4 and a basic lab demonstration before the end of the project.
b. **Demonstration track**: accepts only ideas, which have already passed proof-of-concept and is well into TRL 4. The maturation covers upscaling principles, design of large-scale demonstration, construction, and on-site demonstration with a prototype. Certain technologies have the potential to reach a first of its kind full scale, effectively reaching TRL8.

Figure 7: Project funnel pipe-line, where bubbles indicate projects.



Common for both the Innovation and Demonstration track is the clear stop/go milestone after year 2. Figure 7 illustrates the funnel type innovation model. After the second year, an evaluation will identify the most promising projects to continue.

Monitoring and measurement

Projects will have ambitious goals and create a visible impact in terms of both innovation and potential climate impact. All projects will self-evaluate with specific key performance indicators (KPI) determined by and reported to Steering Committee as part of the stop-go decision. The International Advisory Board will assist the Steering Committee in this task.

Educational roadmap implementation

An educational track is envisaged as an underlying track entangled in the selected projects. The intention is to educate MSc and PhD students, postdoc researchers, and facilitate the potential for spin-out companies. This is expected to result in the creation of SMEs and potential large-scale export businesses. Suitable measures will be taken to ensure that in particular PhD students involved in projects will be able to complete their education even if the initial project does not make it past the stop/go point milestone. An education committee will assist the programme management in this task as well as e.g. advise on strategic issues relating to the build-up of the next generation of CCUS experts.

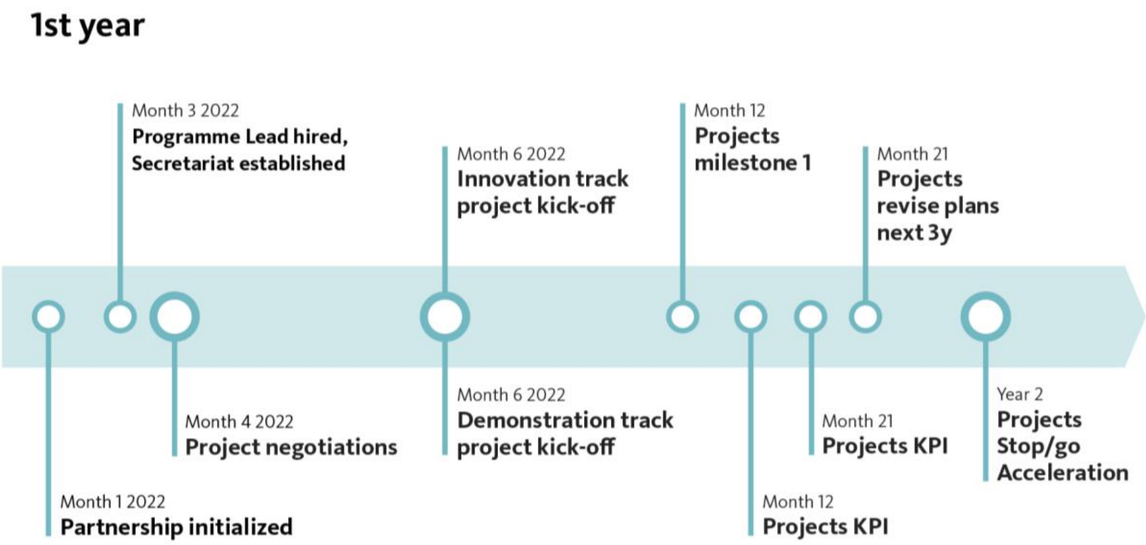
Table 4: 2025, 2030 and 2050 goals that can be backtracked to the actual project activities for the Educational sub-roadmap.

Education Road Map									
Baseline/ challenges				2025 goal			2030 goal		2050 goal
Secure recruitment and talent development	Identify relevant existing courses	Cross institutional courses	Cross institutional and industry PhD programs	Research career in CCUS. Talent program	PhD students with CCUS focus	Formalised cross institutional PhD programme	International educational framework for talents	Educating excellent students in a cross institutional research environment	Leading in international research and teaching of implementing CCUS technologies

Detailed outline of key workstreams and activities in the first year of the Mission CCUS partnership period.

The first two years into the roadmap are illustrated in Figure 8. It outlines the process already from the application negotiations, August 2021 until the stop/go milestones of the first round of funded projects, year 2 into the projects. The technology portfolio, which consists of the Innovation track and the Demonstration track, must consist of a coherent list of projects already in the partnership application. These projects should be ready for initiation after 4 months and manned and active 6 months after the partnership has officially been established. They are expected to describe detailed projects for the first 2 years and a drafted strategy for year 3 to 5.

Figure 8: Timeline for the first year of the roadmap.



First years of the CCUS roadmap in terms of major activities

During the first 2 years all funded projects will benchmark towards self-defined KPIs and more global KPIs defined in the general roadmap partnerships. These are outlined above and are expected to benchmark performance on potential impact and innovation progress. Each project is expected to have milestones aimed at the above instruments. This is indicated by project milestones and KPIs month 12 and 21 in Figure 8.
By month 21 all projects are expected to hand in detailed plans and progress reports which are compared to the total pool of projects. Lighthouse projects are selected, which are allowed to accelerate their development during year 3 to 5 as illustrated in Figure 7. If the Partnership Board finds there is a lack of performance and too few projects qualify as

lighthouses, a second call will be announced seeking new short acceleration projects within the non-allocated funding frame for the years 3 to 5.

Innovation model and educational roadmap

Activities of innovation, entrepreneurship, and education are to be developed and supported within the partnership.

The overarching management structure of the project portfolio in the Mission CCUS roadmap is illustrated in Figure 6. It consists of the two tracks mentioned in the timeline above and an underlying educational track, which maintains an education of relevant researchers, which will support a long-term roadmap towards 2050. Each track is expected to initialise a multitude of projects, which all have an ambition to become lighthouse projects by the end of year 2. A total of 15-20 ambitious projects are expected to be started by the partners.

Phase 1 (stop/go, until year 2): The projects validate existing technologies supported by feasibility analysis, LCA, technology potentials, cost evaluation and general reviews. Both tracks are expected to perform initial feasibility testing in the lab to confirm technology performance. All projects have an active dissemination and communication strategy. All projects are expected to show progress towards concrete and specific KPIs

Phase 2 (implementation, year 3 & 4): After year 2, selected projects are picked for acceleration for maturation into lighthouse activity. The projects are expected to perform detailed designs and construction preparing technologies and knowhow for short- and long-term testing.

Phase 3 (pilots, year 5): Validation of the technologies are reached through lab or onsite testing/demonstrations with pilot applications of the developed knowhow. A clear KPI towards the roadmap success criteria must be followed to secure success of the climate impact.

Success criteria for the Mission CCUS roadmap

The success criteria are partly outlined by the goals indicated for 2025, 2030, and 2050 in Table 1-3 of the sub-roadmaps: Capture, Storage, and Utilization. A general success for all three sub-roadmaps is outlined in the table below.

Success criteria for the Mission CCUS roadmap and sub-roadmaps.
Estimates for 2050 are not feasible for many criteria

	2025 Success	**2030 Success**	**2050 Success**
Total TRL increase	20 projects of each 2 TRL points increase		
New concepts	20	20	
CO2 Centre	1		
OPEX reduction	25 %	50%	
CAPEX reduction	25%	50%	
CO2 emission avoided	0.5 Mtpa	4 Mtpa	5-10 Mtpa
Demonstrations	5	5	
Number of SMEs	3	15	
Resource reduction	25%	50%	
Smart grid	5 collaborations	10 larger collaborations	
Job creation	10 new jobs	40 new jobs	
Produced CO2 products	+1,000 ton CO2e	+100,000 ton CO2e	
Storage capacity	1 Mtpa CO2e	4-9 Mtpa CO2e	20-50 Mtpa CO2e

Risks and Contingency plan

The risk of the overall roadmap mainly originates from the gap analysis presented above in section "Key challenges, inflection points and gaps". This section shows clearly that there are both general risks in terms of political, societal, financial, supply, but also technical risks in terms of cost, knowledge, upscaling, time, and smart grid coupling.

A holistic view on the whole value chain is needed; carbon capture and transportation are prerequisite for carbon storage and vice versa. Links in the value chain can break e.g., if a large supplier of CO2 closes or changes to a non-emitting energy source or if the storage sites volumes are not in-place at the needed time of is the infrastructure does not supply and offtake of CO2 timely. A backup network within the value chain is therefore needed.
The table below shows in brevity the contingency for various important topics for the sub-roadmaps of the Mission CCUS.

Risk and contingency plan in order for the sub-roadmaps to meet the national emission goals over the periods 2025, 2030, and 2050.

Sub-roadmap	**Risk**	**2025 Contingency**	**2030 Contingency**	**2050 Contingency**
General	Lack of political support and funding	Close collaboration with the Ministry	International stakeholder influence	Support from the international environment
Financial	Lack of sufficient funding	Lower ambition for CCUS	EU	UN
Capture	Cost reduction is difficult	Focus on new technologies	Upscaling	Investments
	New technologies are unable to match solvents	Basic science need	More fundamental research	
	Lack of potential CO2 sources		Import of CO2	Import of CO2 & DAC
	Smart grid implementation difficult	Business case optimization	Sector communication	
Storage & transport	Societal acceptance	General information	Stakeholder information	Storage->Utilization
	Offshore field abandonment	Focus on quick implementation	Near shore	Onshore
	Late site maturation	More resource allocation	Use of existing data	
	Well leakage	Well infrastructure surveillance	New technologies	Governmental obligation
Utilization	Biological Technologies are unable to scale up	Detailed FEED	Cross-talk to more fundamental engineering skills	
	Technology is not cost competitive		Longer investment horizon	Subsidiaries
	Export of converted CO2 impossible		EU stakeholder analysis	Global CO2 utilization scheme

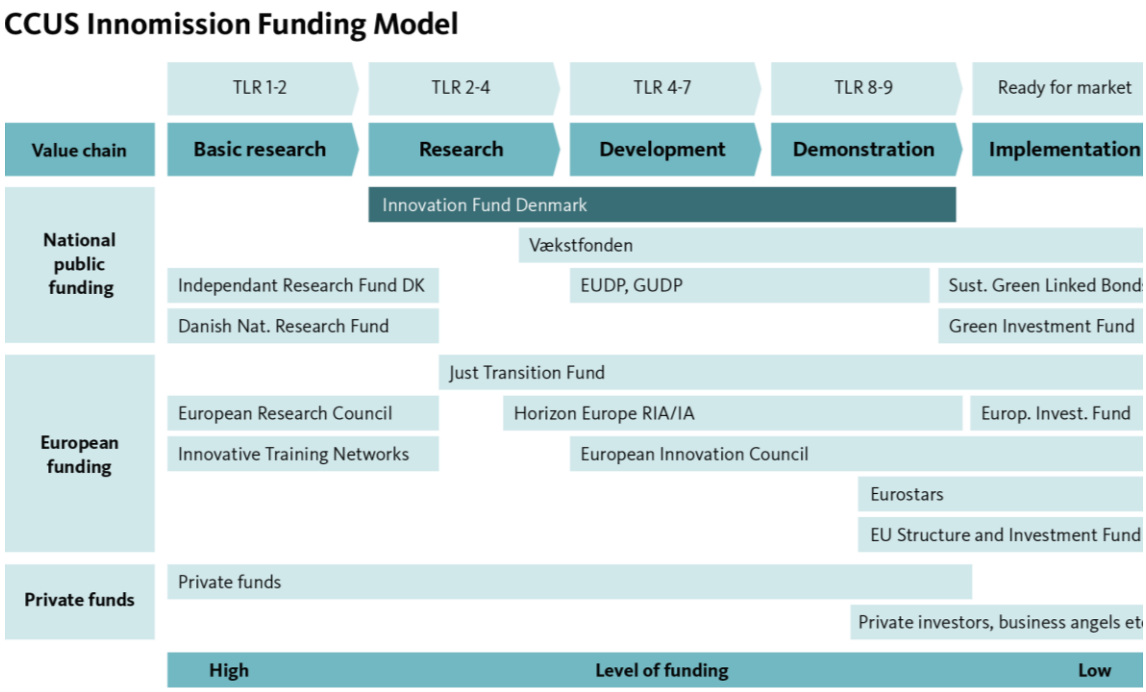
Financial roadmap

Additional funding

During the roll-out of the activities across the entire value chain investments in R&D, innovation, demonstration/upscaling, and at various stages implementation and development of infrastructure will be geared with external funding from national and international sources. Figure 9 gives an overview of the most relevant investment programs ranging from the lowest TRL (basic research) over maturing and demonstration (TRL 4-8) to full-scale implementation (TRL 8-9 and fully fledged technological solutions) at which stage venture capital investments may take over. In addition, funding from the European Recovery Plan and other international funding, e.g. US funding following the MoU between Department of Energy and The Danish Ministry of Higher Education and Science, is an assumed part of the overall financial framework for the CCUS Innomission. This will not only allocate financial support but also secure research collaboration and collaboration on education with strong international partners. The specific mix of funding of the Mission CCUS partnership will naturally depend on the actual partners entering the partnership.

Specific funding for offshore storage options in the roadmap includes the funds made available through the Danish North Sea agreement and administered by the EUDP. From this 197 million DKK is available. Other specific funds for North Sea storage include the Danish Hydrocarbon Research and Development Centre (DHRTC) CO2 Storage Research Programme**.** From this program 10 million DKK/year for three years (2022-2025) will be available for research and development. The EUDP program has additional funding earmarked for CCUS and PtX.

Figure 9: Most relevant CCUS investment programs in relation to TRL.



In order to realise the potential for the technologies to support the national CO2 reduction targets, strategies for short-, mid-, and long-term activities will be initiated.

International links and collaboration

The partners will have a common strategy of engaging international expertise, investments, and research collaborators via existing networks from previous international projects from e.g. EU, the ACT programme, R&D clusters and business relations.

Under the new Horizon Europe programmes and via platforms Danish participation in projects under Cluster 5 "Climate, Energy, and Mobility" as well as in Coordination and Support Actions will secure development, knowledge sharing, public awareness and policies.

Examples of CSAs' are:

- Strengthening Social Sciences and Humanities (SSH) research communities in climate, energy and mobility disciplines
- Accelerating the climate transition in difficult contexts: transition super-labs (pilot)
- Integration of CCUS in hubs and clusters, including knowledge sharing activities
- Support to the activities of the ETIPs and technology areas of the SET Plan (on CCUS)

Furthermore, international platforms, hubs and organisations, e.g. European Energy Research Alliance (EERA), ICDK Boston, will facilitate collaboration on research, innovation and policy with among other Department of Energy, Breakthrough Energy etc.