Carbon capture, utilisation, and storage

Picking the high-hanging fruits of CO_2 mitigation

INSIDE THIS WHITE PAPER

STATE OF GREEN

Connect. Inspire. Share. Think Denmark

stateofgreen.com

CARBON CAPTURE, UTILISATION, AND STORAGE
Picking the high-hanging fruits in CO_2 mitigation

Version 1.0
November 2022

FRONT PAGE PHOTO
Unsplash

EDITOR IN CHIEF
State of Green

EDITOR IN CHARGE
State of Green, info@stateofgreen.com

CONTRIBUTERS

The Danish Energy Agency, Henrik Sulsbrück, hesu@ens.dk
The Danish Energy Agency, Morten Skovgaard Olsen, msdo@ens.dk

Innovation Center Denmark v/UM, Camilla Sofani Bartholdy, cabart@um.dk
Invest in Denmark, Charlotte Katrine Melchiorsen, chamel@um.dk

Green Power Denmark, Michael Madsen, mma@greenpowerdenmark.dk
Green Power Denmark, Vibeke Højberg Strebøl, vhs@greenpowerdenmark.dk

Confederation of Danish Industry, Henrik Skou, hesk@di.dk
Confederation of Danish Industry, Stella Bücker, stbu@di.dk
CCS Alliancen, Finn Lauritzen, fla@axcelfuture.dk

DOWNLOAD THIS WHITE PAPER
Download this white paper and other related publications at www.stateofgreen.com/publications

FOR MORE INFORMATION
To order copies of this white paper or receive information about other related publications, please contact State of Green at info@stateofgreen.com

Executive summary

Containing the global rising temperatures to a 1.5 degrees increase requires lowering the CO_2 concentration in the atmosphere drastically. There are many talks to be walked in decarbonising society. Some need to be addressed individually, and others necessitate collaboration - collaboration across value chains and borders. With carbon capture, utilisation, and storage (CCUS), leaps can be taken and barriers can be broken.

Partnerships spurring collaboration across borders
With the Danish tradition of conducting public-private partnerships and high levels of societal trust, the recipe for a proven way of devising solutions to sustainable development challenges successfully is written. It has been followed before with the rise of the international offshore wind industry. Those learnings and guiding principles can prove valuable once again in developing CCUS as an international opportunity that can support a global green transition.

.. and across the full value chain
Denmark has experience in all corners of the CCUS value chain; from highly efficient combined heat and power plants, waste-to-energy facilities, and an energy-efficient industry, to a strong transport sector, district heating grids for utilisation of excess heat, and cutting-edge technology providers. Denmark also boasts a world-known track record for research and development, helping new industries well underway. To execute it all, great attention is put towards educating a skilled labour force, ensuring a transition that is both green and just. But we are not quite there yet.

Renewable solutions for green ambitions
Denmark is blessed with an underground that has previously been exploited for oil and gas. With the government putting an end to the extraction, and optimal conditions for storing CO_2 in the same oil and gas fields, the way is paved for Carbon capture and storage (CCS). Denmark has a high share of renewable electricity, which is crucial for the production of green hydrogen. Together with the aforementioned Danish competencies across the energy value chains, Denmark has a great foundation for utilising CO_2 (CCU) in the production of e.g. e-fuels and plastics. Combine a recipe that works with cutting edge prerequisites with an ecosystem that has more than 50 years of experience, and the world has a New Nordic industry emerging.

About this white paper
This white paper sets the scene with a global burning platform. All reliable science points to decarbonisation of the atmosphere as the key solution to transitioning towards a more sustainable society. It takes the reader chronologically through the fundamental value chain and presents how and why Denmark is geared to advance a green transition and mitigate CO_2 hard-to-abate emitters, to the benefit of both the planet and the people who inhabit it.

Carbon capture, utilisation and storage – deep decarbonisation of society

BY EXECUTIVE VICE-PRESIDENT FRANS TIMMERMANS, EUROPEAN COMMISSION

Russia's brutal and unjustified war in Ukraine has created an unprecedented situation on Europe's energy market, with soaring energy bills that are increasingly problematic for households and businesses across the continent. The energy crisis requires our immediate attention, but as we focus on the problems at hand, we must not lose sight of our horizon. The climate and biodiversity crises are here, and they will not go away simply because there are other urgent issues to address. Every Member State has committed to make Europe the first climate-neutral continent by 2050 and to deliver our contribution to keeping the global temperature increase limited to 1.5 degrees.

With REPowerEU, the European Commission set out our response to Putin's weaponisation of energy. The plan ensures the EU becomes independent from Russian fossil energy while still delivering on our climate commitments. Alternative supplies, higher energy savings and, above all, a massive acceleration in the deployment of homegrown renewable energy are at the centre.

In several ways, REPowerEU changes the playbook for Europe's energy transition. In the immediate future, certain Member States will use more coal than projected. Gas, on the other hand, is losing its role as a transition fuel. EU-wide targets for energy efficiency and renewables are set to higher levels than previously proposed, more funding is channelled towards energy carriers like green hydrogen, and targeted changes to permitting procedures will enable the necessary acceleration in rolling out wind, solar, and other renewables.

While the EU is quickly turning the page on fossil fuels, carbon capture, utilisation, and storage (CCUS) projects remain building blocks on our way to climate neutrality. By 2030, 5Mt of CO_2 should be removed annually from the atmosphere and permanently stored through technological solutions. With CCUS projects funded by the Emissions Trading System-based Innovation Fund and a dedicated plan on "Sustainable Carbon Cycles", European support for CCUS has grown over the years. The Commission is currently working on an EU regulatory framework for the certification of carbon removals, to develop robust and transparent carbon accounting rules. This proposal, which is expected for the end of this year, will ensure that carbon removals are credible and have the desired effect.

Europe's green transition requires safe and sustainable CCUS to reduce CO_2-emissions from hard-to-abate and energy-intensive industry processes, and to remove carbon from the atmosphere. With renewable energy as the pillar of our energy transition and CCUS technologies to complement this transition, we can create new business opportunities and make both the European energy system and economy more resilient.

Frans Timmermans
Executive Vice-President, European Commission

A match made in the Danish underground

BY KRISTOFFER BÖTTZAUW, DIRECTOR GENERAL OF THE DANISH ENERGY AGENCY

CCUS is a core technology in the Danish green transition on the road to Denmark's 70 percent reduction target, and onwards to climate neutrality by 2050. At the same time, utilisation and storage of CO_2 has the potential to ensure a just transition by supporting employment in the same local areas, and for some of the same professional groups, as the oil and gas sector previously provided.

The Danish ecosystem has unique conditions for capturing, utilising, and storing CO_2. The Geological Survey of Denmark and Greenland (GEUS) calculates that the Danish subsoil can contain up to 22 billion tonnes (GT) of CO_2. This corresponds to between 500 and 1000 years of total Danish emissions at the current level - more than enough for other countries to exploit as well.

Turning an old technology into an evergreen
Carbon capture and storage (CCS) is neither an unknown nor untested technology. On the contrary, for well over 100 years, technologies that can capture CO_2 have been used. Since the 1920s, the air has been purified of CO_2 in submarines and since the 1960s in spacecraft. By utilising the captured CO_2 (CCU) - combining it with green hydrogen – e-methanol and e-kerosene can be made for fuelling our heavy industry, maritime fleet, and aviation. Green hydrogen can be made with clean power from wind turbines through the electrolysis of water.

The Intergovernmental Panel on Climate Change (IPCC) and the Danish Climate Council point to CCUS as an important means of fulfilling the Paris Agreement. Both because it can help decarbonise hard-to-abate emissions, and because it can remove CO_2 from the atmosphere through the capture and storage of biogenic CO_2.

International partnerships are key
It is not small things that are needed. According to the International Energy Agency (IEA), by 2060 we must capture and store more than 100 billion tonnes of CO_2 in total to meet global climate and energy goals.

Denmark accounts for 0.1 percent of global CO_2 emissions. In driving the global path to net zero, Denmark's national efforts can offer great inspiration. Inspiration that stands on the shoulder of societal efforts, underlining why public-private collaboration is essential in the quest to develop technologies, policies, and partnerships to accelerate the green transition. That is why we share our experience from the Danish energy transition with 24 countries across the world. By partnering with some of the world's biggest emitters, and fastest-growing economies, we put our expertise to use where it holds the greatest impact. We focus our efforts on Danish core competencies within energy transition.

This whitepaper shows how Denmark is geared to reap the benefits of carbon capture, utilisation, and storage, and how the efforts can drive the green transition globally by working together.

I hope you will feel inspired.

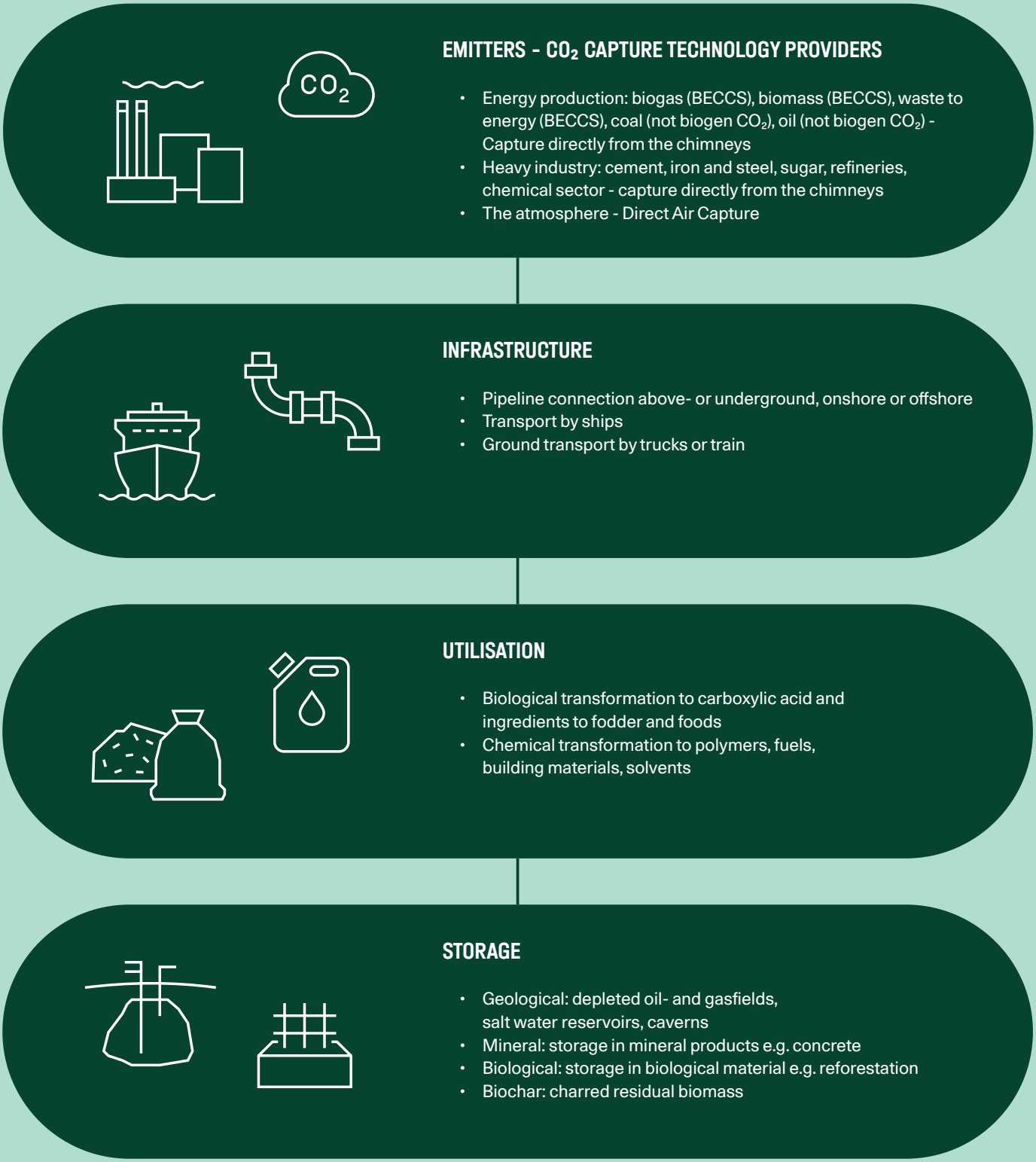
Kristoffer Böttzauw
Director General of the Danish Energy Agency

Index

FIGURE 1

The carbon capture, utilisation, and storage value chain

The value chain is not explicit for the whole sector and this whitepaper presents just a range of the capabilities



CHAPTER 1

Explaining carbon capture, utilisation, and storage (CCUS)

CCUS is the process of collecting/capturing (C) waste carbon dioxide (C) and transporting it to a site, where it is either used (U) for alternative purposes or stored (S) in geological formations.

The purpose of CCUS is to prevent the release of large amounts of carbon dioxide (CO_2) into the atmosphere, but also to make biogenic CO_2 a valuable green commodity.

Today, carbon can be captured from the smoke from industries and from heat and power plants and waste-to-energy facilities, or it can be separated from biogas plants instead of being emitted into the air.

One way of capturing CO_2 is to conduct it through long pipes down to a liquid, which, among other substances, consists of additives that help absorb the CO_2 in the liquid. Once the CO_2 has been absorbed in the liquid, it can be separated and utilised for alternative purposes, or stored underground – onshore or offshore.

Storing CO_2
Storing CO_2 is done by pumping the carbon into the many small cavities of the underground, while the above clay layer acts as a lid. As stated earlier, the Danish underground can store between 500 and 1000 years of the total Danish emissions at the current level.

CO_2 utilisation
If the captured biogenic carbon is put to use, it can be synthesised into green fuels, which can fuel aircrafts and the maritime fleets of the future. When utilising the captured CO_2, the CO_2 is recycled and thereby prevents other emissions from fossil fuels. CO_2 is already a valuable commodity and today the world uses 230 million tonnes (Mt) of CO_2 from fossil fuel sources each year, according to the International Energy Agency.

What picking the high-hanging fruits means
When referring to picking the 'high-hanging fruits', it is because many of the 'low-hanging fruits' in the green transition have already been picked. Denmark has more than 50 years of experience doing just that. In particular in the sectors that can be retrofitted or directly electrified with relative ease.

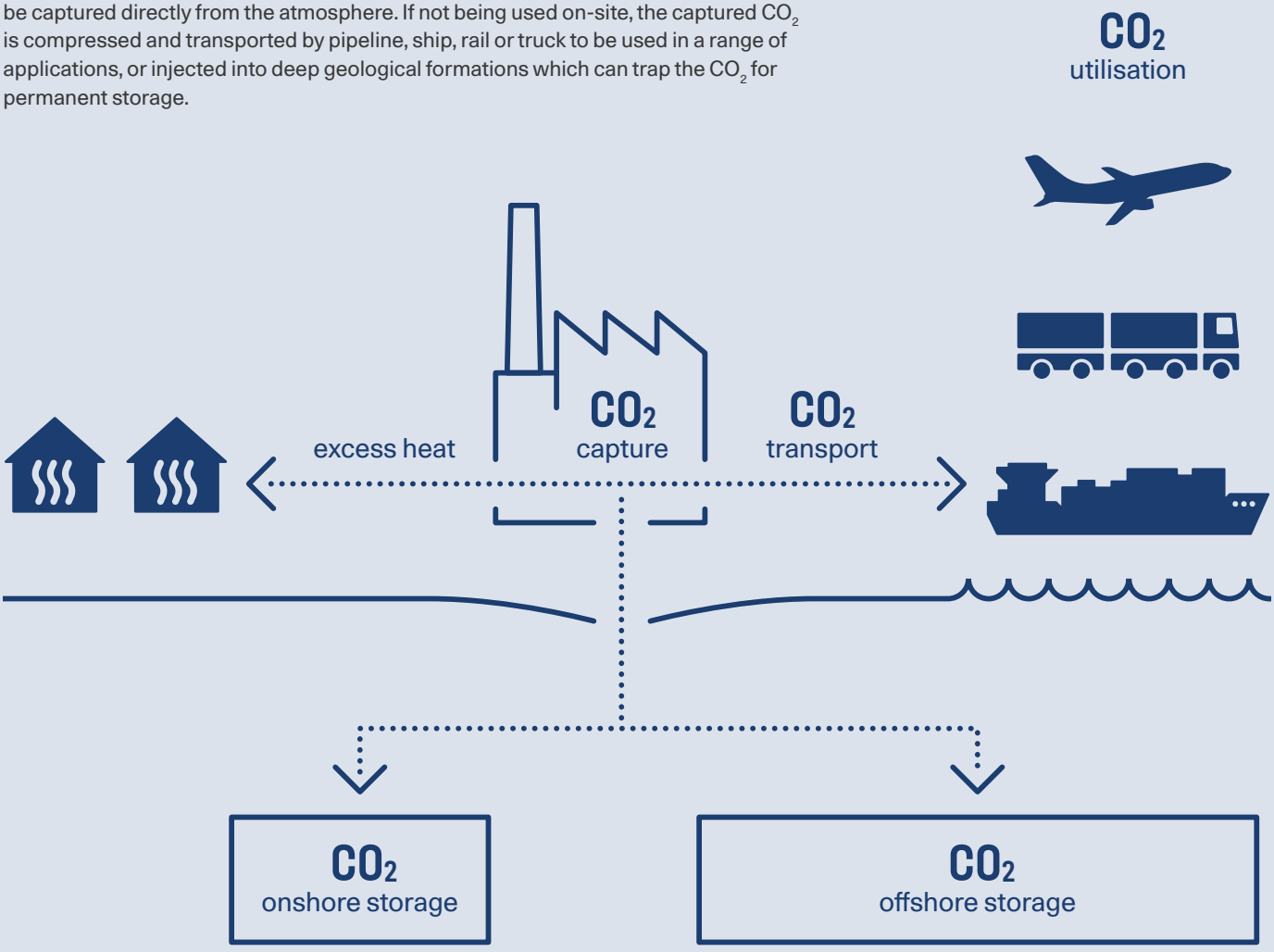
CCUS is a key enabler of deep decarbonisation of the hard-to-abate sectors/the high-hanging fruits. They include transportation, agriculture, and heavy industry such as cement and chemical production.

Those who have the greatest prerequisites, hold the greatest responsibility. That is why Denmark and other countries are aiming to make CCUS a viable solution to meet global climate ambitions.

FIGURE 2 - EXPLAINING CCUS

Carbon capture, utilisation, and storage

CCUS involves the capture of CO_2 from large point sources, such as power generation or industrial facilities that use either fossil fuels or biomass as fuel. The CO_2 can also be captured directly from the atmosphere. If not being used on-site, the captured CO_2 is compressed and transported by pipeline, ship, rail or truck to be used in a range of applications, or injected into deep geological formations which can trap the CO_2 for permanent storage.



Adapted from Technical University of Denmark (DTU)

CHAPTER 2

Policy regulations: developing the framework for a new industry

A marked-based, technology-neutral pool and stable framework conditions will leapfrog CCUS technology and innovation.

With the Danish Climate Agreement for Energy and Industry of 22 June 2020, the Danish Parliament decided that the capture, utilisation, and storage of CO_2 is an important piece in achieving Denmark's climate policy goals.

A market-based, technology-neutral pool was established to promote the CCUS. The pool is planned to be phased in from 2024 and ultimately amounts to EUR 109.5 million annually.

With the Climate Agreement, it was decided to establish central framework conditions supporting the development of CO_2 capture, transport, utilisation, and storage in Denmark. At the same time, the agreement helps to ensure a stable framework for a new industry in Denmark, and to ensure that society gets a share in any potential gains when shared resources are used.

A national strategy paves the way for development
In the agreement, it is defined that the two sub-agreements in the national CCUS strategy from June and December 2021 must prepare permits for storing CO_2, from 2025 for Denmark to be a potential international buyer of captured CO_2 in the first disbursement of the incentives.

With the CCUS strategy, the framework is set for disbursing EUR 2.2 billion in public funds. Through the green sub-agreement under the Finance Act, EUR 269 million were also set aside to support CO_2 capture from biogenic sources. In the fund of the Danish Green Tax Reform, EUR 2.4 billion was allocated to CCS.

Support in two phases
The support will be divided into two phases. **The first phase** will be implemented in the short term to kick-start the market. The incentives will support the emitters' investments in developing the facilities to capture the CO_2 they emit.

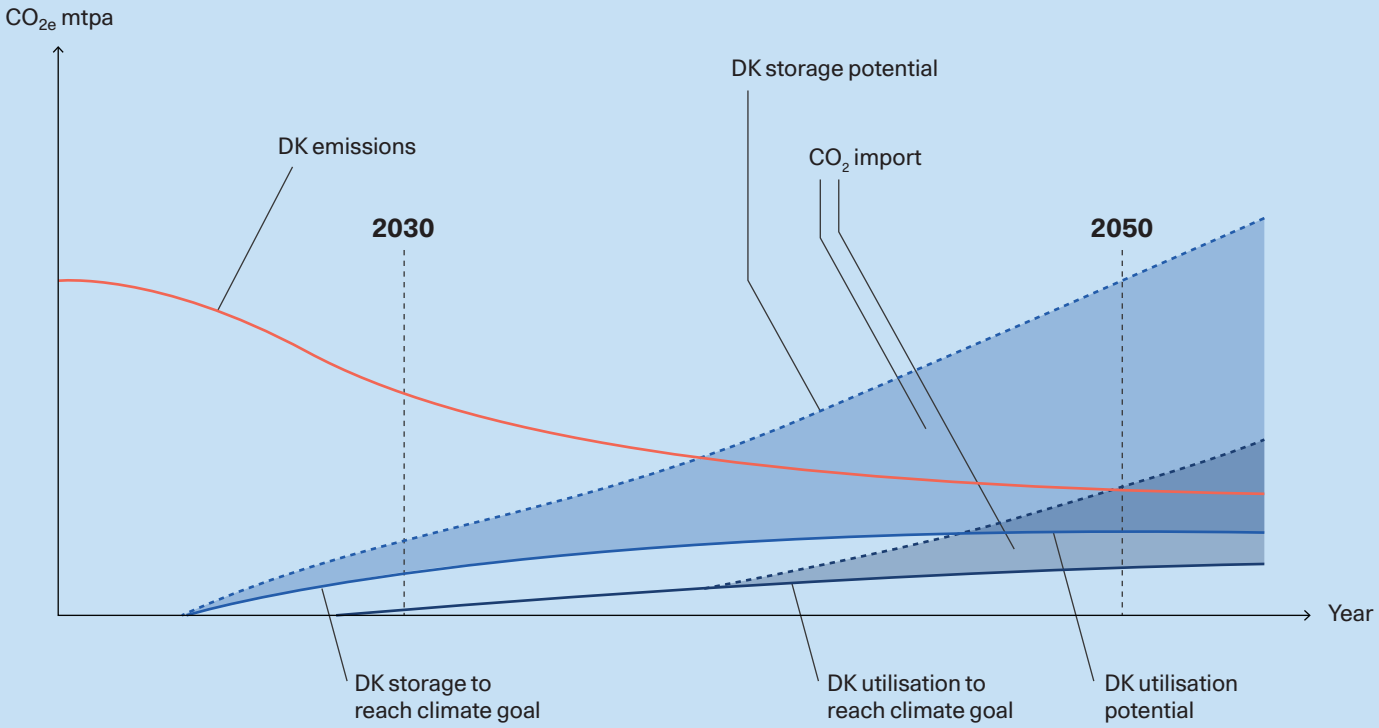
In connection with the realisation of the CCUS pool in **phase two**, it will be investigated how the utilisation of CO_2 can contribute to the climate goals. In March 2022, the parliament agreed upon a Power-to-X strategy, which addresses the use of CO_2 for developing green hydrogen based solutions.

Forward-looking framework conditions for CO_2 storage
Increasing demand for CO_2 storage capacity is expected in Northern Europe, and here the Danish underground can contribute significantly to the Danish and European climate goals. To share any future gains from CO_2 storage, the state will become a co-owner of permits for Danish CO_2 storage. At the same time, taxing CO_2 storage, including that which takes place in the Danish part of the North Sea, will become possible.

FIGURE 3

Vision of CO_2 reductions towards 2050 and beyond

With the right political support and societal acceptance, Denmark may contribute to reducing CO_2 globally, while at the same time building business potential. Denmark has a massive opportunity to store tonnes of Mtpa CO_2. CCU is still a relatively immature and costly technology. However, ongoing research and development will make it gradually more important as a substantial contributor to the 2050 net-zero target. Denmark has the potential to build a business case on conversion of imported CO_2 into valuable products that can be exported.



Adapted from The INNO-CCUS Partnership

CHAPTER 3

Capturing CO_2 from energy-efficient emitters

Any pathway to mitigate climate change requires a reduction of CO_2 emissions. Carbon capture holds part of the key to drive CO_2 emissions to zero and beyond.

While some action has already been taken to mitigate climate change, most of the action has been focused primarily on eliminating emissions, e.g. by improving energy efficiency or electrifying processes with renewable electricity. However, to achieve the goal of climate neutrality, there is the debatable need to remove substantial (gigatons) amounts CO_2 from the atmosphere every year for decades to come.

Carbon capture technologies capture CO_2 either directly from the atmosphere or at a point source of emission. The most efficient way to capture CO_2 is from carbon point sources such as heat and power plants, waste-to-energy facilities and industrial plants as the concentration of CO_2 at a point source is much higher than in the atmosphere. Depending on the origin and use of the captured CO_2, the captured CO_2 can either result in climate-neutral emissions or even climate-negative emissions.

CO_2 from hard-to-abate sectors
Hard-to-abate sectors include industries where complete decarbonisation is prohibitively costly or technically impossible based on currently available technologies. Emissions from these industries are often related to the physical processes themselves, e.g. when limestone is transformed into cement. By capturing CO_2 from these processes, it becomes possible to make hard-to-abate sectors climate neutral.

CO_2 from biogenic sources
Sources of biogenic CO_2 cover plants using sustainable biomass, biogas plants, and biogenic waste. In other words, biogenic CO_2 originate from biological sources and are included in the natural carbon cycle. Hereby, the biogenic CO_2 becomes valuable for several uses: It can be removed completely from the atmosphere by storing it in the underground (negative emissions) or it can be used to avoid CO_2 emissions in other sectors by transforming the CO_2 into valuable climate-neutral products such as green fuels and green plastic.

Denmark has great potential to lead the development and implementation of carbon capture as several biogenic carbon point sources are located in Denmark. However, shortages of CO_2 supply are expected in the future, as the demand for carbon storage and utilisation is increasing, and the supply of CO_2 from point sources is decreasing due to optimisations and decommissioning of power plants.

Capturing CO_2 from point sources is a first and important step towards climate neutrality. Yet, the point sources alone will not drive the world's CO_2 emissions to zero. Therefore, new ways of capturing CO_2 from the atmosphere must be developed and matured rapidly and within the next decade. In Denmark, research in direct CO_2 capture is ongoing but it is still in its infancy and on a low technological readiness level. Several larger research investments in Denmark are aiming to change that.

FIGURE 4

CCUS matrix

CCUS is a proven technology with the potential to reduce emissions from hard-to-abate sectors. Depending on the source and the usage of the CO_2, the technology can either help remove carbon from the atmosphere, make heavy industries carbon-neutral or be a platform for producing carbon-neutral products such as green fuels and green plastic.

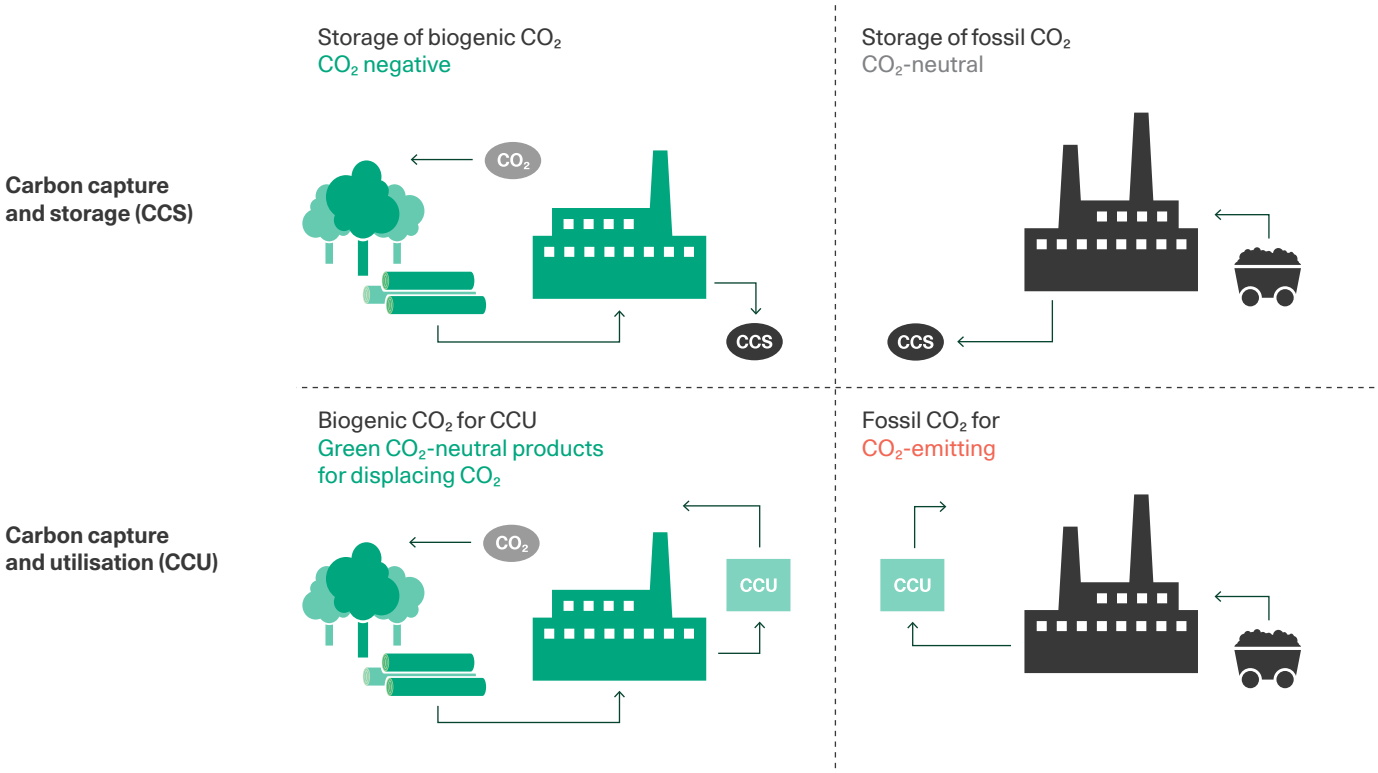


Photo credit: Amager Resource Center

Carbon capture with net-zero energy consumption

In 2021, the waste-to-energy facility Amager Resource Center (ARC), in Copenhagen, established the first pilot plant for carbon capture in Denmark. The primary purpose of the plant was to test carbon capture technologies and to reduce the net energy consumption needed for the carbon capture process. This is done by focusing on energy optimisations of every step in the process and integrating it into the district heating production at ARC. The aim is to achieve the cheapest possible carbon capture.

At the end of 2022, the pilot plant will be followed by a demonstration plant that is able to capture 500 kg CO_2 every hour. The demonstration plant will simulate a full-scale plant and hereby provide knowledge and experience in relation to operation and maintenance.

CONTRIBUTORS

Amager Resource Center, Danish Technical University, Rambøll, Pentair, EUDP, Green Power Denmark

CHAPTER 4

Driving innovation and development with public-private partnerships

Public-private partnerships are a hallmark of the Danish way of turning climate change measures into policies, tangable climate action, and long-term commitments.

Since the 1970s, Denmark has had a tradition of enacting agreements with broad consensus across the political spectrum on energy and environmental policy issues.

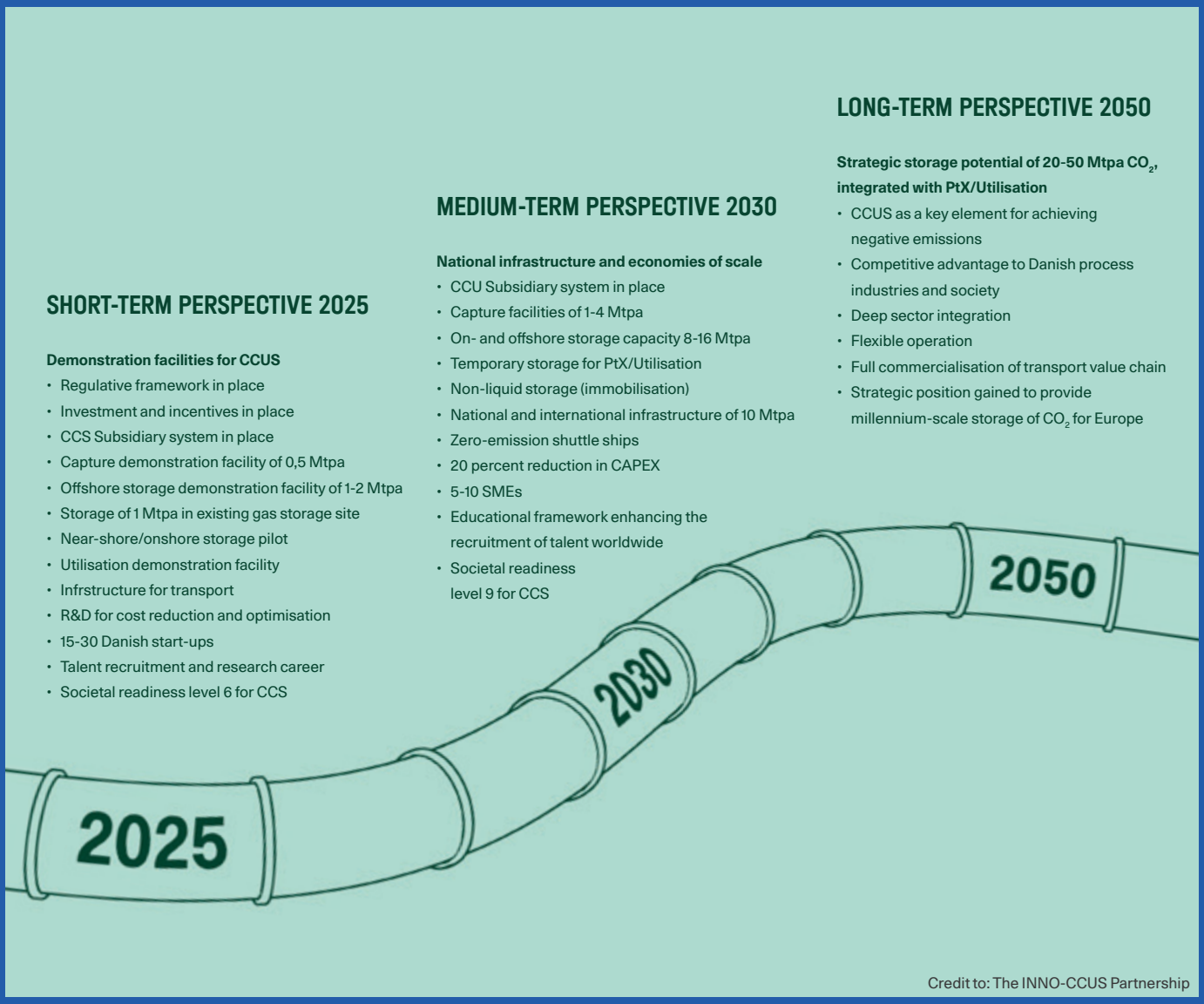
Effective public-private partnerships have allowed changing Danish governments to enact regulations and programs with the support of business and industry, ensuring successful implementation and adherence. While the public sector provides the ambitious long-term goals and stable framework conditions, the private and academic sector supplies the innovation, solutions, and investments needed to achieve the visions. Among other significant achievements, it was this public-private synergy that paved the way for a global wind industry that has put Denmark on the green world map.

50 years of experience
Through 50 years of working across professional boundaries, Denmark has learnt that effective sector integration requires a pragmatic approach and an experimental mindset. But even more crucial, it comes back to stability and trust.

Commercialisation of CCUS requires developing a new infrastructure, where an inter-sectorial, long-term model for cooperation between public and private stakeholders is pivotal. Both financial perspectives and business model perspectives depend on regulatory frameworks which are determined by the government. Efforts to reduce risk and uncertainty have a positive effect on the willingness to invest, the access to capital and steer the focus towards R&D and infrastructure in the industry.

A thriving science environment
When it comes to research and development in green technologies, the rewards of a whole-of-society approach also stands out. Today, Denmark boasts several companies that hold global leading positions in the energy and environment industries, and no other OECD country displays a similar development of green technology measured in patent applications.

The centre of the green transition
Being neither a silver bullet nor a standalone, the Danish story is simply a testimony that trust, continuity, and binding commitments are paying dividends. As such, it speaks loud and clear to the power and potential of placing public-private partnerships and global cooperation at the centre of the green transition.



Credit to: The INNO-CCUS Partnership

The Green CCUS Roadmap: towards a fossil-free future

A wide-ranging green CCUS partnership, with 54 different actors. The partners are public and private actors, including universities, knowledge institutions, and large and small companies, working together on implementing a Danish CCUS roadmap. The plan is to focus on short-term (2025), medium-term (2030), and long-term (2050) solutions that will contribute to Denmark achieving its climate goals while at the same time supporting the establishment of new green industries, export opportunities, growth, and jobs.

The partnership and roadmap are supported by Innovation Fund Denmark which, based on the Danish Finance Act 2021, has been tasked with investing a total of approximately EUR 100 million in mission-driven green partnerships – including carbon capture, utilisation, and storage.

CONTRIBUTORS

The INNO-CCUS Partnership, State of Green

The Danish Government's Climate Partnerships

Denmark's 14 industry-specific Climate Partnerships, initiated by the government in 2019 is instrumental to realising Denmark's 2030 climate target of reducing CO_2 emissions by 70 percent, compared to 1990 levels. Spanning from energy and finance to construction and transport, industry leaders have been tasked with formulating each sector's contributions to carbon reductions. In simple terms, it is a green roadmap for the industries by the industries. The unique collaboration between industry and government in the climate partnerships has been a catalyst for companies to look beyond their own industries for green solutions and innovative partnerships.

The eight partnerships for Aviation, the Maritime sector, the Land transport sector, the Energy and utility sector, Food and agriculture, Manufacturing, Waste, water and circular economy, and the Energy intensive industry, are all very vocal about the need for developing CCUS as a key solution, in meeting the Danish CO_2 reduction target.

Collectively, the Climate Partnerships have produced more than 400 recommendations on how to reach the target, many of which are being integrated into national policy.

CONTRIBUTORS

State of Green

CHAPTER 5

Connecting the dots with a developed and modern infrastructure

Be it as a waste product or as a valuable commodity, moving CO_2 from a to b to c, or in other words from CC to U or S, requires an integrated infrastructure. One that simultaneously connects the Danish value chain and connects the rest of the world to Denmark.

CO_2 can be transported in many ways: by rail, truck, ship and pipeline. Important CO_2 hubs in Denmark can be placed in Denmark's effective and accessible ports, but also close to the largest CO_2 emitters or to the Danish electricity transmission grid.

CO_2 transport by ship is possible by transporting CO_2 either from major Danish ports or from other countries to storage sites in the North Sea. From the east, Denmark will be a convenient storage partner for large emitters from countries around the Baltic Sea. From the west, CO_2 can be shipped directly to storage in the Danish part of the North Sea. CO_2 transportation by ship is not yet an established business, contrary to e.g. LNG shipping. In order to transport sufficient quantities on each ship, the CO_2 must be liquefied by a combination of cooling and a pressure of approximately 20 bars. In comparison, LNG ship tanks are designed to a pressure of 6-7 bars. The tanks on a CO_2 ship must therefore be constructed with thicker walls, making the tanks heavier and more difficult to load and unload.

CO_2 is transported through pipelines by the pressure created by compressor stations. Similarly, the capture process is by itself a major source of energy use. But due to the widespread Danish central heating system, which heats approximately two thirds of all Danish households, Denmark has an opportunity to use excess heat from these processes.

Developing national infrastructure
A planning process has been initiated by the Danish Ministry of Climate, Energy and Utilities that will tie together Danish emitters, ports and CCU facilities in a Danish CO_2 pipeline system. This system can be a combination of smaller plastic pipe connections at the local level and bigger transmission pipes. The bigger pipes may connect the Greater Copenhagen area with one or two onshore or near-shore storage sites in Zealand, and the Aalborg area with one or two onshore or near-shore sites in Jutland. A third pipeline can be a direct link from Nybro at Jutland's North Sea coast to storage sites in the North Sea.

... and international infrastructure
In a European context, Denmark will cooperate with other countries in order to receive foreign CO_2 and store it in the Danish underground. To this end, bilateral agreements have been reached with the likes of Belgium, the Netherlands and Germany. Denmark will also cooperate with other North Sea countries that have large storage capacities and may share a combined North Sea pipeline infrastructure.

The world's first carbon capture shipping entity

Dan-Unity CO_2 has been established by the two Danish shipping companies, Evergas and Ultragas, and will be the world's first carbon capture shipping entity. Standing on the shoulders of the two companies' rich histories, Dan-Unity CO_2 will tackle the challenges of today to create a better tomorrow.
Evergas and Ultragas are among the world's leading seaborne transporters of gases and liquids. Their focus is to make gas transport simple and safe, and to set new standards for efficient and sustainable gas transport at sea. Dan-Unity CO_2 will carry the CO_2 under the most energy-efficient transportation, which is a mixture of a pressure of 6.5 bar and minus 48 C.

Dan-Unity CO_2 is a partner in the Greensand project and has recently, in cooperation with Carbfix, been awarded EUR 115 million from the European Innovation Fund to build the Coda terminal in Iceland. Here, Dan-Unity CO_2 will design, construct and operate CO_2 carriers. Starting in 2026 it will move up to 3 Mtpa for permanent mineralisation in the underground.

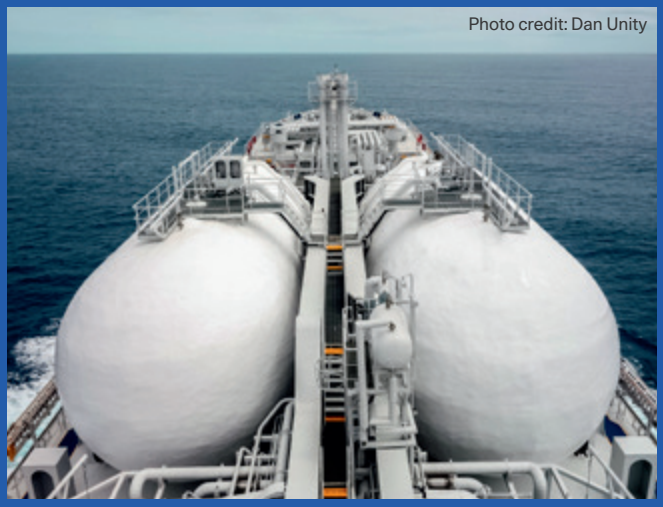


Photo credit: Dan Unity

CONTRIBUTORS

Dan Unity, CCS Alliancen,
Confederation of Danish Industry

Reengineering the gas grid for the future

Evida is a state-owned shareholder company with approximately 450 employees. Their main office is located in Viborg, Jutland.

For more than 35 years, Evida has operated the Danish gas distribution grid comprised by 18.000 kilometres of pipelines and ensuring safe distribution of methane to more than 400.000 consumers. Over the last 8 years Evida has adapted more than 50 green biogas plants into their system thereby increasing the pace of the Danish green transition. The biogas supply covered 25 percent of the Danish gas consumption in 2021 and is expected to reach 100 percent around 2030.

Building upon this experience, Evida has been granted some degree of freedom by its owner, the Danish Ministry of Finance, to expand into other areas than natural gas, such as CO_2. Evida has now put forward a strategy supporting the Danish ambitions with respect to PtX and CCUS through pipelines for hydrogen and CO_2. Evida expects to reuse methane pipelines and thus decrease costs and speed up the green transition. Evida will be able to receive and use "patient" capital that can decrease long-run costs.


Photo credit: Evida

CONTRIBUTORS

Evida, CCS Alliancen, Confederation of
Danish Industry

CHAPTER 6

Utilising CO_2

Biogenic CO_2 is an important feedstock for climate-neutral fuels and plastics. As an example, utilising captured carbon in the production of e-fuels is carbon neutral because the carbon is recycled. The consumption of e-fuels can have a further positive climate impact as it can substitute the use of fossil fuels.

Emitted CO_2 has traditionally been treated as a form of waste. However, carbon capture and utilisation (CCU) technology enables us to turn CO_2 into valuable climate neutral products.

The climate neutral products are produced by combining captured CO_2 with green hydrogen. The hydrogen is extracted from water using electrolysis powered by electricity. It is important that the electricity used in the process is renewable, e.g. from offshore and onshore wind, solar or power plants using sustainable biomass. It is equally important that the carbon used comes from biogenic sources so that the process stays within the natural carbon cycle and does not add new CO_2 to the atmosphere.

Producing hydrogen-derived E-fuels
CCU is particularly relevant when decarbonising the heavy transport sector and the plastics industry. By adding carbon to hydrogen in a synthesis process, e-diesel, e-methanol and e-kerosene can be produced. These fuels can directly replace fossil fuels currently used in hard-to-abate sectors like heavy road transport, shipping and aviation. Furthermore, e-methanol can be used as a core ingredient in the plastics industry. Climate-neutral plastic also has the advantage that the CO_2 is bound in the material for many years.

The technology is not only decarbonising fossil sectors, it also offers increased sector integration and provides flexibility and security of supply at the same time. Furthermore, sector integration can lower the price of climate-neutral products.

Great conditions for sector integration
Denmark has a world-class energy system with great conditions for sector integration. For instance, excess heat from electrolysis and synthesis plants can be used in the district heating system. Additionally, Denmark has access to large amounts of renewable electricity from offshore wind in the North Sea and Baltic Sea, and biogenic carbon from point sources such as biomass plants, biogas plants, and biogenic waste. These conditions make Denmark the obvious place for pursuing CCU.

Large scale projects and more to come
Denmark already has great ambitions for production of climate-neutral fuels and plastic. Currently, projects of at least 7 GW of electrolysis production by 2030 have been announced. Collaboration across the entire value chain is needed to realise these ambitions. Danish companies are already leading the way, both in the implementation of CCU and in the green transformation of the entire society.

Green Fuels for Denmark: a PtX partnership

Power-to-X (PtX) is a cornerstone technology in the fight against climate change in hard-to-abate sectors and a clear, homegrown European industrial strength. With Green Fuels for Denmark, the aim is to contribute to decarbonising road, maritime and air transport.

By 2027, Green Fuels for Denmark will produce green fuels enough to supply the whole domestic fuel demand for aviation in Denmark. Currently, the first phase of Green Fuels for Denmark is progressing, and will be able to supply 1,000 tonnes of renewable hydrogen for heavy road transport annually. By 2030, when fully developed, Green Fuels for Denmark aims to reach a total electrolysis capacity of 1,300 MW and to produce 275,000 tonnes of renewable fuels per year.

Behind Green Fuels for Denmark is a unique partnership covering the whole PtX value chain from development to off-take. The partnership covers both private and public entities as well as knowledge institutions. The experiences and know-how embedded in the partnership are vital to the success of the project and the scale up of the Danish PtX industry. Green Fuels for Denmark has just been granted status as an IPCEI project (Important Project of Common European Interest) by the European Commission as one of two Danish PtX projects.

Green Fuels for Denmark is located in Copenhagen, Denmark, at Ørsted's combined heat and power plant, Avedøreværket.

CONTRIBUTORS

Ørsted, Project Green Fuels for Denmark, Green Power Denmark

FIGURE 5

CCU explained

Carbon capture and utilisation is a conversion technology that turns electricity into carbon-neutral products such as green fuels or green plastic. Renewable electricity is used to produce hydrogen in electrolysers. The hydrogen can either be used directly or it can be processed further into carbon-neutral products in synthesis units by combining the hydrogen with biogenic carbon. Excess heat from the electrolysis and synthesis plants can be used for applications such as district heating.

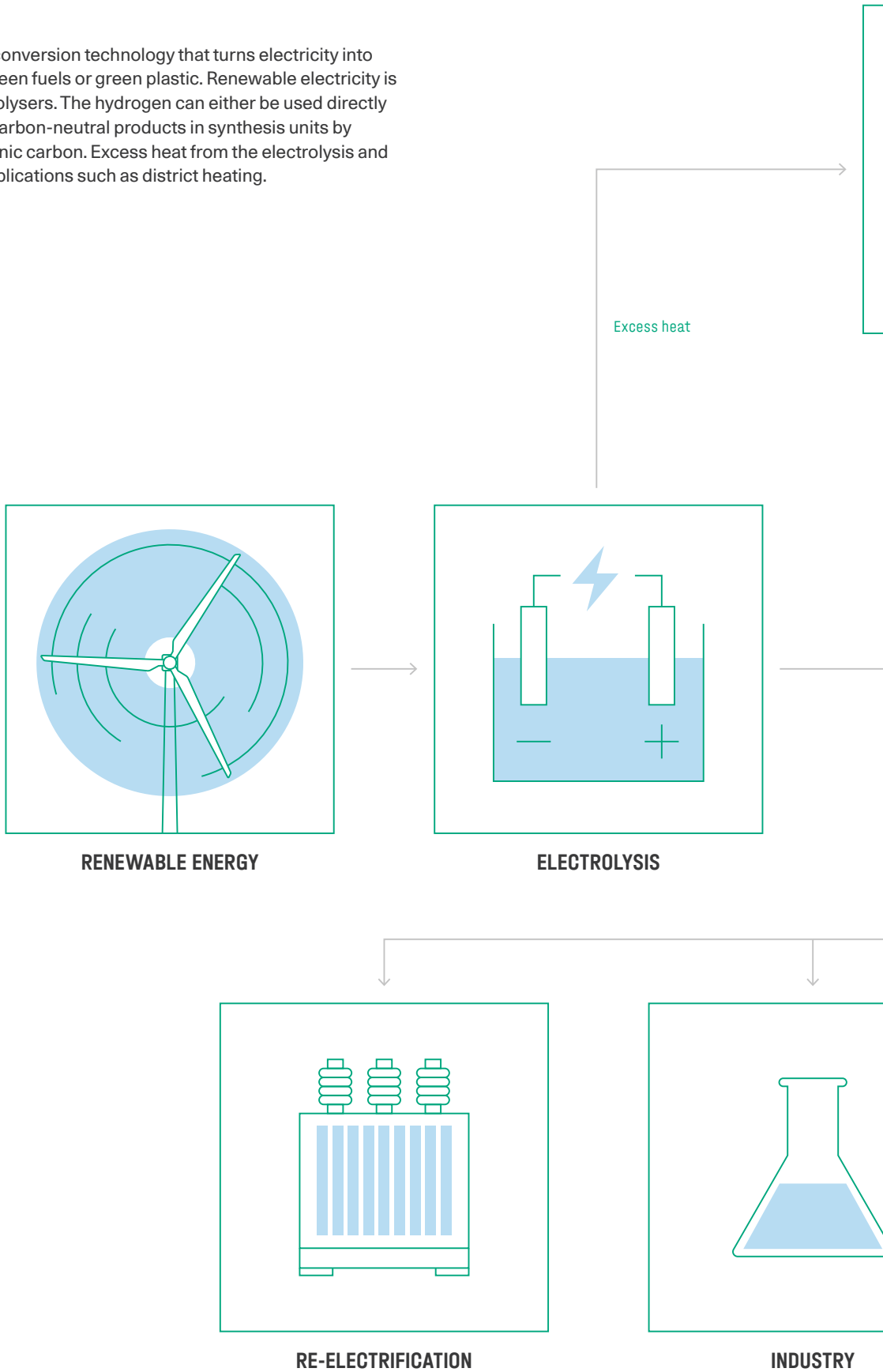
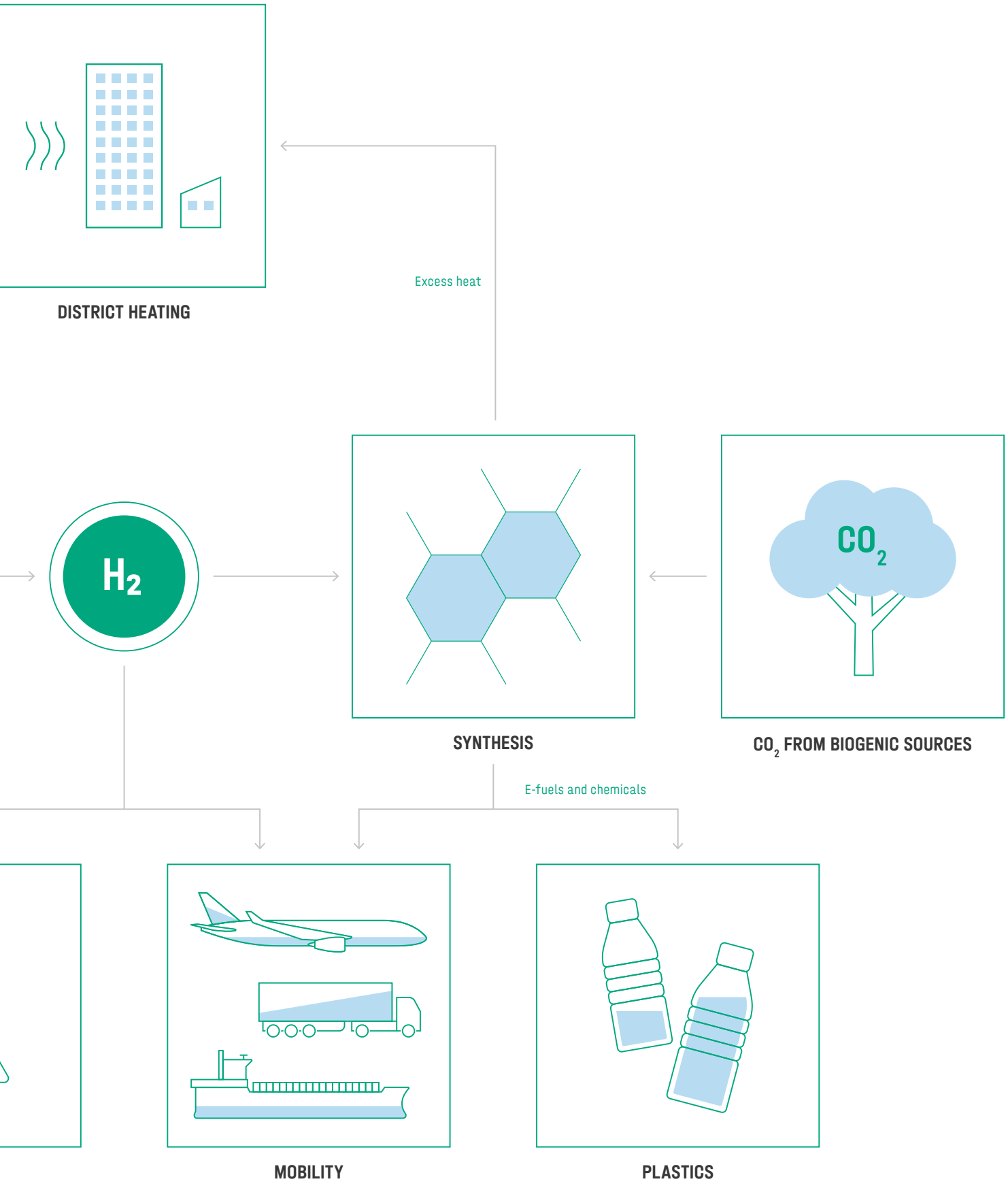


Figure adapted from Rambøll


DISTRICT HEATING
Excess heat
H_2
SYNTHESIS
CO_2
CO_2 FROM BIOGENIC SOURCES
E-fuels and chemicals
MOBILITY
PLASTICS

CHAPTER 7

Storing CO_2

The Danish subsoil holds a large storage potential of up to 22 billion tonnes of CO_2. This potential - combined with other factors - makes Denmark an ideal location for CO_2 storage.

The ambitious and dedicated CCS roadmap developed by the Danish Ministry for Climate and Energy includes significant public funding and support as a cornerstone in Denmark's green transition.

Denmark has a strong history of public support for energy solutions turning climate ambitions into sustainable industries as previously proven in the Danish wind industry. This extensive experience can and should serve as a lever for realising the Danish CO_2 storage potential.

Benefiting from the Danish underground
Furthermore, Denmark is geographically well placed in Northern Europe with a central location in the North Sea and holding shallow waters, enabling cost of efficiency and sector integration. On top of that, the efforts to drive down CO_2 emissions are likely to remove or transform the 14,000 Danish jobs that are currently employed in the oil and gas sector. This underlines the importance of the ensuring a green AND just transition. Estimates show that a targeted investment in CCS could create and maintain around 3,200 new Danish jobs - jobs that require many of the same skills as in the oil and gas sector.

Overall, Denmark is expected to be able to store CO_2 both offshore, nearshore and onshore. The Geological Survey of Denmark and Greenland (GEUS) has been commissioned to undertake geological and seismic investigations of possible storage sites in the Danish underground. Hereafter, the Danish Energy Agency will make strategic environmental consequence reviews of the sites. A selection of the sites is expected to be opened in 2024 for a tender of rights for interested parties to undertake more detailed, in-depth investigations of storage possibilities. CO_2 storage may begin in these sites from 2027 or 2028.

How to store the CO_2
CO_2 storage is done by pumping CO_2 into the underground under high pressure up to 2 or 3 km below surface. The pressure needed is higher the deeper the CO_2 is stored. Several Danish companies have the competences and experience to be part of the value chain as operators, sub-suppliers or technical advisors.

Denmark has both infrastructure and competencies available for CO_2 and hydrogen transportation. Very large wind power ressources are available, enabling renewables integration in the work processes.

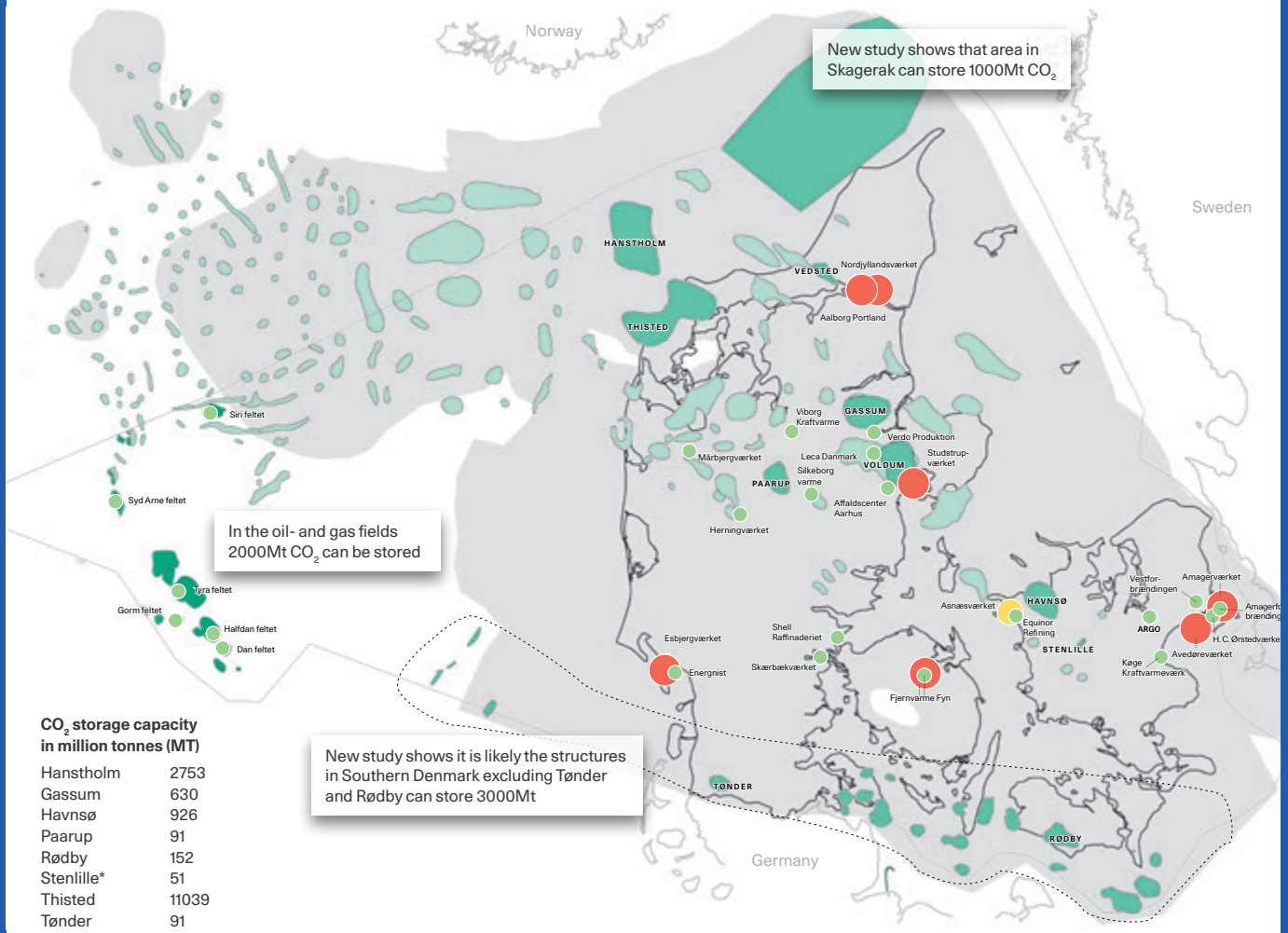
Supporting the CCS value chain
Adding to that, agreements on CO_2 import and export are being negotiated and finalised as per the end of 2022, providing flexibility and scale and supporting an innovative and cost-efficient CCS value chain.

CCS Alliance

The Confederation of Danish Industry, Danish Shipping, the Danish District Heating Association, the Danish Metalworkers' Union, Danish Offshore, and Axcelfuture have established the CCS Alliance. They bring together +50 public & private partners covering the entire value chain to build a strong and competitive CCS industry. The aim of the Alliance is:

- To work for the highest amount of capture and storage capacity in 2030, including an understanding and acceptance of what this requires in terms of political measures
- To strengthen public, private, and political awareness of CCS
- To share knowledge along the entire value chain
- And to highlight the importance of creating a framework for a competitive Danish CCS industry with jobs for Danish workers.

Denmark from above



CO_2 storage capacity in million tonnes (MT)

Hanstholm	2753
Gassum	630
Havnsø	926
Paarup	91
Rødby	152
Stenlille*	51
Thisted	11039
Tønder	91
Vedsted	162
Voldum	288
Syddanmark	3000
Olie-gasfelter	2000
Skagerrak	1000
Sum	22.183

*In use as natural gas storage

The largest point sources for CO_2 emissions in Denmark

Fossil fuels and biomass

- 100.000 - 500.000 tonnes
- 500.000 - 1.000.000 tonnes
- > 1.000.000 tonnes

Geological structures

- Investigated areas
- Unexplored areas
- Sandstone 800-3000m
- Oil-gas fields

Gas Storage Denmark: secure storage solutions

Gas Storage Denmark (GSD) is a publicly owned company responsible for underground storage. In the last 30 years, GSD has stored natural gas in facilities on Zealand and in Jylland. Energy storage is a crucial part of the green transition, and GSD is focused on establishing storage solutions for hydrogen and CO_2, which will be key contributions to a greener society. Storing onshore requires close contact with neighbours and local stakeholders, and GSD works closely together with these partners as well as with national partners and customers. In GSD's facility in Stenlille on Zealand, GSD will be able to permanently store 500.000 tonnes CO_2 pr. year from 2025. GSD has a very strong focus on security, high standards and efficiency.

CONTRIBUTORS

Gas Storage Denmark, CCS Alliancen, Confederation of Danish Industry

Photo credit: Ineos, Project Greensand

Greensand: from depleted oil fields to CO_2 storage

There is a huge potential for storage of carbon in the depleted oil fields in the Danish part of the North Sea. INEOS Energy is leading the partnership behind the Greensand project, which will be among the first to demonstrate the entire CCS value chain for climate purposes in Europe. CO_2 captured at the INEOS Oxide site in Antwerp, Belgium, will be transported by ship to the Danish part of the North Sea to the Nini offshore platform more than 150 km from the coast of Jutland, where it will be injected into one of the existing wells. The planning is progressing according to plan and the first injection of CO_2 is expected by the end of 2022. The full project could be operational from the end of 2025.

The primary objective of the Greensand project is to safely and permanently store potentially between 0,5 and 1,5 mill tonnes of CO_2 in 2025 and up to 8 mill tonnes of CO_2 per annum from 2030 in the INEOS operated Siri area. The storage potential, if achieved, will contribute significantly to Denmark's 2030 overall emissions reduction target.

CONTRIBUTORS

Ineos, Project Greensand, CCS Alliancen, Confederation of Danish Industry

Photo credit: TotalEnergies

Bifrost: long-term CO_2 storage in the North Sea

Project Bifrost explores a long-term solution for CCS by using existing infrastructure in the Danish North Sea owned by TotalEnergies, Noreco, Nordsøfonden (offshore fields and associated facilities) and Ørsted (pipelines). The aim is to store 3 Mtpa of CO_2 around the Harald gas field more than 200 km from the coast of Jutland. This field is expected to be able to store CO_2 from 2027 or 2028.

Bifrost will develop an offshore floating unit as an intermediate storage- and injection facility to which CO_2 is transported by ship. The project will also repurpose existing gas-pipelines for CO_2 transport from shore. Additionally, Bifrost will advance monitoring technologies and protocols and understanding of the socio-economic aspects of CCS. The project will be key to unlock the CCS potential in the North Sea, meet Denmark's climate targets and create new jobs for the offshore workforce.

CONTRIBUTORS

TotalEnergies, Project Bifrost, CCS Alliancen, Confederation of Danish Industry

CHAPTER 8

Attracting foreign talent and developing business opportunities with CCUS

Attracting bright minds and foreign investments play an important role in the establishment of a thriving CCUS scene in Denmark.

Technology and innovation are building blocks for a global green transition. Denmark can become an ideal living lab for CCUS, fostering innovation and testing new technologies.

Attracting foreign talents and global companies is needed to gather the skills and fill the gaps in the existing workforce, which will ultimately be beneficial to the economy. It is essential to ensure Danish companies', researchers' and institutions' continued and improved competitiveness, and to help secure Denmark's position as a leading knowledge society.

Taking leadership on innovative solutions means a strong collaboration between businesses and universities, as well as developing a talent-pool of highly qualified labour. Denmark offers flexible business conditions and an internationally-oriented workforce. By building a nationwide CCUS ecosystem, Denmark can become a key location for CO_2 storage and utilisation.

Testing and scaling up
The Danish commitment to the clean energy transition means a stable and predictable framework for long-term investments. It also means access to a variety of actors across the full supply chain in related sectors like renewable energy production, green hydrogen, Power-to-X and sustainable fuels for trucks, shipping and aviation.

Denmark's advanced position on biomass-fired combined heat and power plants, biogas, solid waste incineration and cement production means companies have good local opportunities for testing and commercialising carbon capturing solutions on these carbon sources and creating the foundation for subsequent technology exports to other countries.

Moving from being CCUS entrepreneurs of innovation to growing business opportunities requires identification of investment potentials and public-private commitment to scale up solutions.

New solutions to be commercialised
The use of carbon capture depends on several factors including technology development, commercial viability, alternative fuel prices and availability, and future emission-related regulatory requirements. Further analyses and developments are required to maximise emission reduction and minimise costs, as well as developing business models that would allow utilisation and/or storage of the carbon capture.

Although the emissions reduction potential of CCUS is significant, its CO_2 abatement costs are currently high. The incentive structures need to be in place working efficiently to demonstrate market-based success.


RAJ
MIDAS

Photo credit: Kasper Hornbæk

Direct Air Capture (DAC) in Denmark

Direct Air Capture is a needed tool for Denmark's goal of net neutrality both in combination with utilisation and storage, but it is still in its infancy regarding both implementation and research. The energy, water, and heat demand of existing technologies make large-scale implementation undependable and unreliable for long-term solutions. Right now, the estimated cost is between 400-1000 EUR (t CO_2 output/year). Denmark is investing heavily to develop new technology and methods to lower input requirements and costs of DAC.

The Novo Nordisk Foundation CO_2 Research Center (CORC) is an example of Denmark's strong research landscape. CORC is an interdisciplinary research center, located at Aarhus University, with a mission to research and develop technology that is able to capture and convert carbon on a gigaton scale. It was awarded 630 million DKK (85 mil EUR) in 2021 and is one of Denmark's biggest investments in green technology. The aim is to combine life science with chemistry to explore new methods for DAC and carbon conversion for utilisation.

CORC aims to mature new DAC technology to higher TRLs in record time by early-on implementation of established businesses and policymakers to bridge the gap between ideas and scaleup. CORC employs the best research groups around the world as satellites to Aarhus University to ensure the best competencies in the field of carbon conversion and capture.

CONTRIBUTORS

The Novo Nordisk Foundation CO_2 Research Center (CORC), Green Power Denmark

Northern Denmark's joint beacon of green growth

Through CO_2Vision, North Denmark aims at becoming a regional frontrunner for CCUS. Their CO_2Vision derives from an ambitious and wide-ranging partnership, consisting of more than 50 private companies, organisations, educational and research institutions, and business developers.

Their vision is that in 2030 North Jutland is an international pioneer region for CO_2 capture, utilisation and storage, where CO_2 is captured from the 50 largest CO_2 point sources. At the same time, a green piped infrastructure system has been established for the transport of both hydrogen and CO_2.

The infrastructure can be accessed by companies for transport and use, which enables the largest emitters in the region to capture emissions and gives other companies the opportunity to produce products incl. green fuels for heavy transport and the aviation sector. At the same time, several intermediate storage facilities have been established at ports, for example, and CO_2 and hydrogen are stored underground in suitable structures.

By 2030, 5,000 new jobs will be created in the industry for CO_2 capture, use and storage.

CONTRIBUTORS

Project CO_2 Vision,
State of Green

Learn more about Danish energy solutions,
find more cases from around the world
and connect with Danish experts:

www.stateofgreen.com

STATE OF GREEN IS A NOT-FOR-PROFIT, PUBLIC-PRIVATE PARTNERSHIP FOUNDED BY:

Confederation of Danish Industry

Danish Agriculture
& Food Council

GREEN
POWER
DENMARK

Ministry of Industry, Business and Financial Affairs

Danish Ministry of Climate,
Energy and Utilities

Ministry of Environment
of Denmark

Ministry of Foreign Affairs
of Denmark