Direct Air Capture i Danmark

En pixibog om vejen til negative CO2-emissioner i 2050

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Direct Air Capture in Denmark

A white paper on the path to negative CO_2 emissions in 2050

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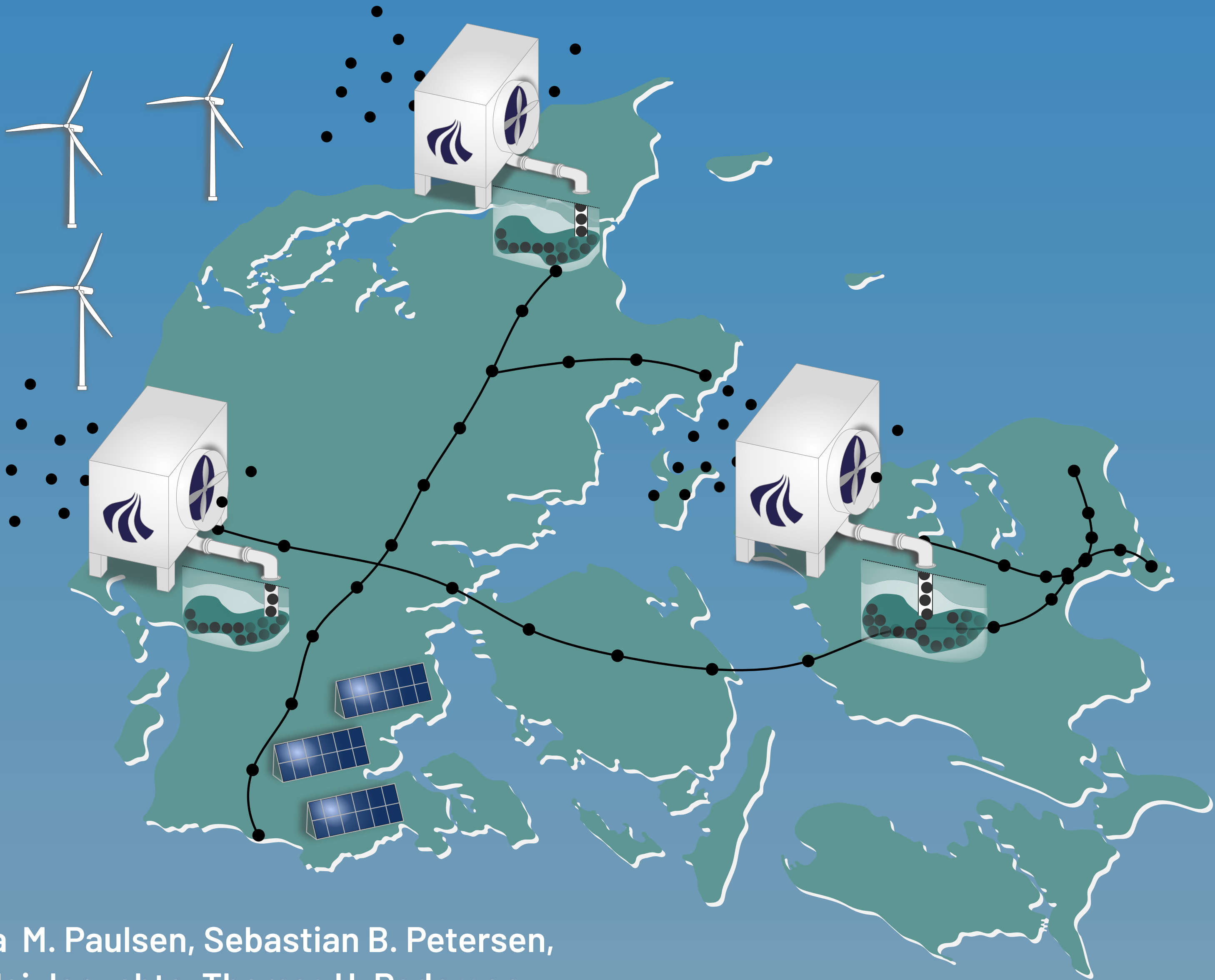

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Preface

Direct air carbon capture and storage (DACCS) is one of the few technologies that can be used to remedy the past sins of greenhouse gas emissions by delivering negative CO_2 emissions. The purpose of this white paper is to present what we believe is the current status of DACCS in a Danish context. In this regard, we describe the resource consumption of water, energy, and land to achieve the Danish goal of 110 % greenhouse gas reductions by 2050. Additionally, we discuss the most critical challenges of implementing DACCS in Denmark.

We also aim to challenge the dogmatic thinking that has characterized the discussion on DACCS and have the ambition to create a common foundation for future dialogue. Furthermore, we present an action plan for the development of the technologies and the political framework conditions.

This white paper is based on our research, which began with the INNO-CCUS partnership in 2022. It should therefore be seen as the first edition of a reference work that evolves with the development of DAC.

The publication has received support from the Danish Energy Technology Development and Demonstration Programme (EUDP) and Innovation Fund Denmark, whose contributions have been crucial to our work. We hope that our efforts will contribute to a more nuanced discussion about DACCS and its potential in Denmark.

Happy reading!

INNO-CCUS
Carbon capture, utilisation and storage

Innovation Fund Denmark

EUDP

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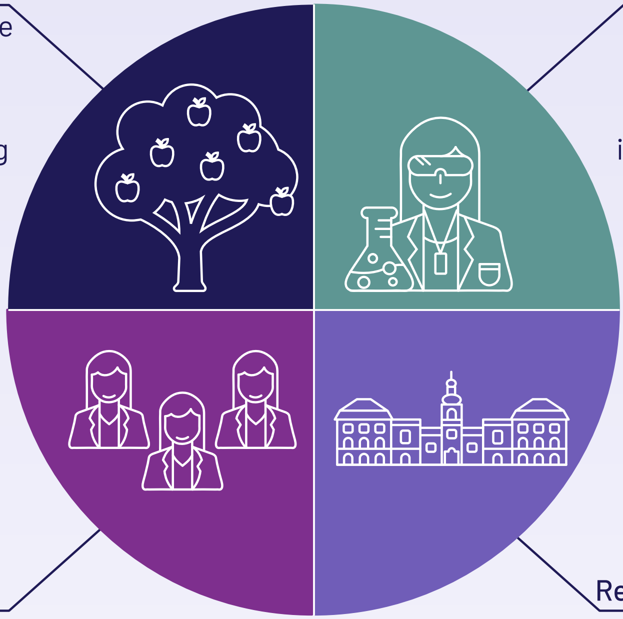
Summary

The necessity of DACCS

DACCS is necessary for the sustainable realization of the 110 % target, even though it is a high-hanging fruit.

Technical recommendation

Next-generation DAC technologies need to be demonstrated to increase investor optimism and gain experience for further development of the technologies



Market recommendation

Economic incentive structures should be implemented to promote the development of DACCS.

Regulatory recommendation

A national carbon strategy should be developed to ensure sustainable use of biomass and guarantee additionality.

A detailed list of recommendations can be found on page 31.

Denmark's 110 % goal

Denmark has set an ambitious target to achieve a 110 % reduction in greenhouse gases by the year 2050.[1] The goal is essentially to create a climate-positive society that absorbs more greenhouse gases than it emits. This way, we can compensate for our historical emissions and potentially reverse global warming.

Figure 1 shows Denmark's historical emissions in CO_2 equivalents since 1990, as well as the projected future emissions based on achieving the 110 % target. With the current targets, Denmark is expected to be CO_2-neutral by 2045.

In the following pages, we will discuss how achieving the 110 % target would look when CO_2 is captured directly from the atmosphere using DACCS (*direct air carbon capture and storage*).

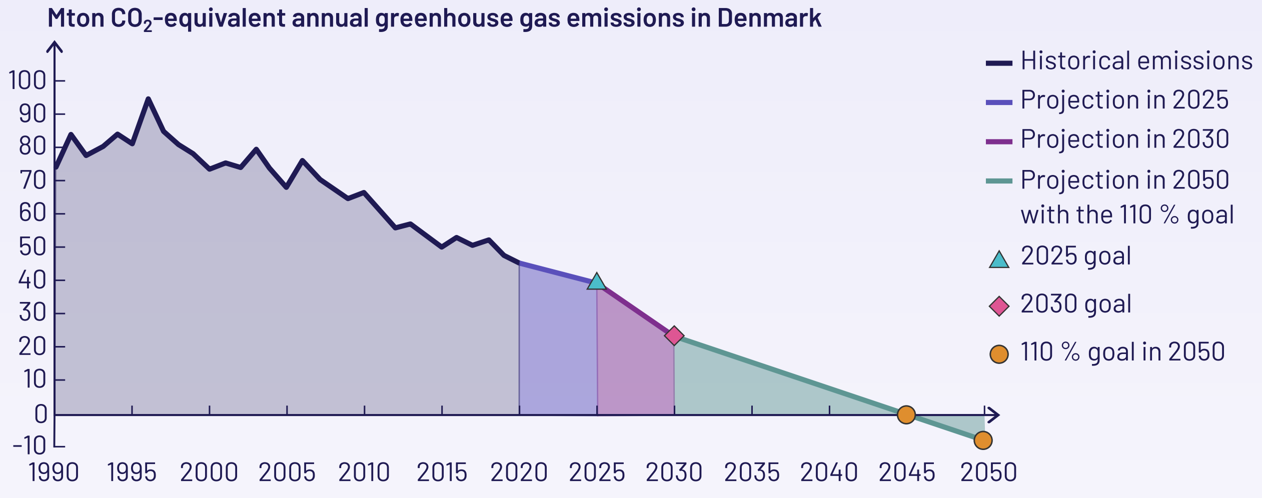


Figure 1: *Denmark's national historical emissions and projections as a result of the climate targets.*[2]

The DAC dogma

DAC encompasses several technologies that, through the use of electricity and heat, can capture CO_2 directly from the air. These technologies then permanently store the captured CO_2 underground, thereby creating negative emissions. The CO_2 captured from DAC can, in principle, also be used for other purposes, but that is another story.

One of the advantages of DACCS is that its reduction potential is essentially only limited by the availability of renewable electricity production. This contrasts with other technologies that offer negative emissions, where the availability of biomass is the limiting factor. Furthermore, DACCS benefits from being location-independent, allowing installations to be placed close to storage sites or pipeline infrastructure.

However, DACCS in Denmark is often met with a nearly dogmatic skepticism in the debate, based on a misunderstood premise of the technology's justification.
So, let us make it clear:

- DACCS should not be a licence for the continued use of fossil fuels!
- DACCS is not in competition with CO_2 capture from point sources, such as waste incineration and cement production, where CO_2 can be removed from ongoing emissions much more efficiently.
- DACCS should be seen as a supplement to methods that reduce our emissions — not as a replacement.

The implementation of DACCS technologies is not a low-hanging fruit in achieving climate neutrality. There are several methods that are more feasible in the near future, as illustrated in Figure 2.

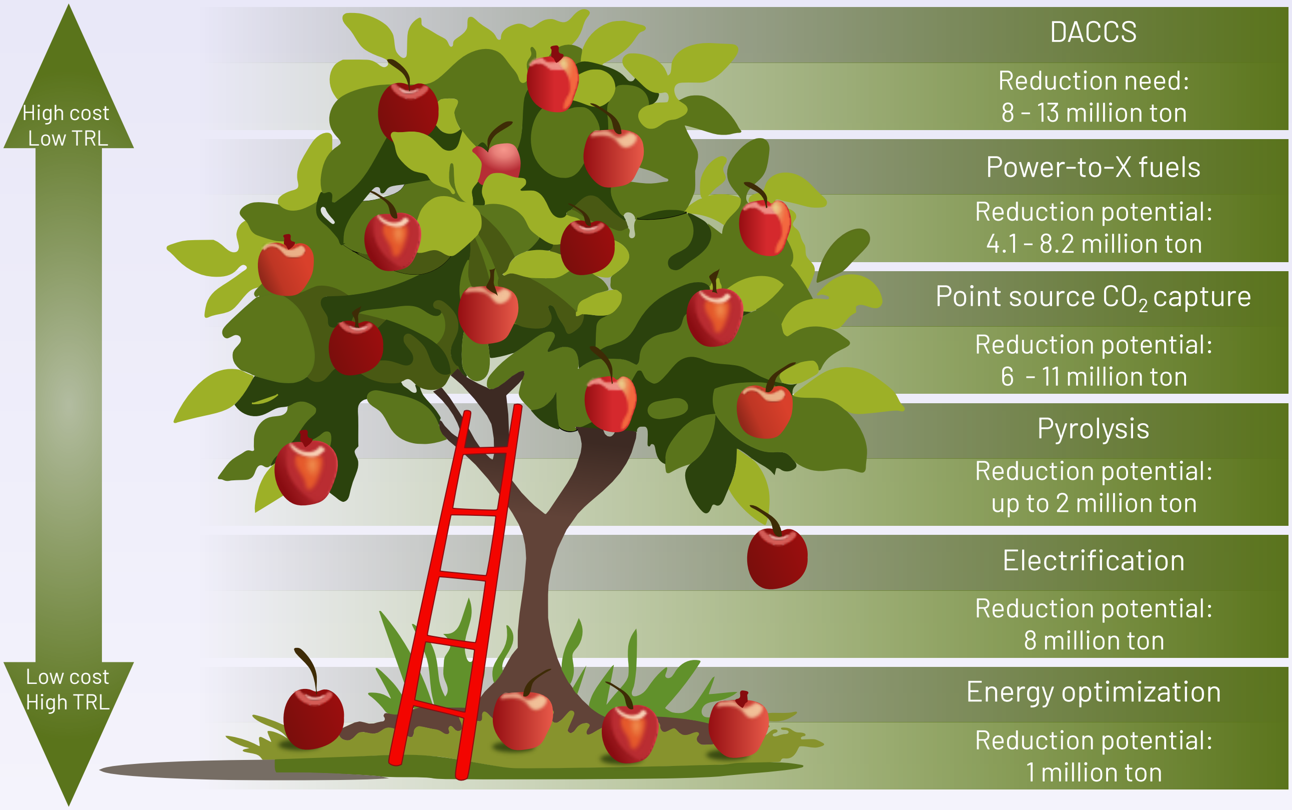


Figure 2: *The potential of various technologies for reducing greenhouse gases ranked by technology readiness level (TRL) and cost.*[2,3]

DACCS will play a crucial role in the future when we aim to completely halt greenhouse gas emissions and start addressing past emissions. This is because DACCS is one of the few methods that can directly contribute to a negative CO_2 balance, thereby addressing both historical emissions and the residual emissions that are realistically unavoidable in the future.

Residual emissions

Residual emissions refer to the amount of greenhouse gases with negative climate impact that cannot be reduced and therefore must be removed using negative emissions technologies. These residual emissions originate from sources such as methane and nitrous oxide emissions from agriculture, biogas leaks, composting, wastewater, and non-energy-related emissions from industries like cement production.

Historical emissions

Historical emissions are the total amount of greenhouse gases that have already been released into the atmosphere since the beginning of industrialization. The additional 10 % of CO_2 that Denmark aims to remove each year after 2050 is based on Denmark's greenhouse gas emissions in 1990. These historical emissions are significant, having contributed to the current levels of greenhouse gases in the atmosphere and already negatively impacting the climate.

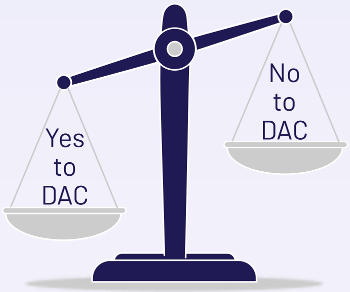
Is DACCS needed in Denmark?

Negative emissions can essentially be achieved through afforestation, BECCS (*bioenergy with carbon capture and storage)*, pyrolysis, and DACCS.

Nature absorbs CO_2 through photosynthesis and stores it as biomass. If the biomass is harvested and used for energy purposes, such as producing liquid fuels or combustion for heat production, it can qualify as BECCS if the released CO_2 is captured and stored underground. The advantage of BECCS is that there is a good business case for producing the energy initially, and the CO_2 emissions can subsequently be captured in a relatively high concentration. However, the potential of BECCS, like afforestation, is limited by the available amount of biomass and the demand for biomass-based energy.

Pyrolysis is a process that stores carbon from biomass into biochar, which can be plowed into fields to serve as a CO_2 sink. In addition to biochar, pyrolysis produces green gas and oil, which can be used for energy purposes and contribute positively to the economic feasibility of the process. The potential for biochar also depends on the availability of biomass resources.

Afforestation, BECCS, and pyrolysis are all methods that rely on biomass, a limited resource. Although BECCS and pyrolysis have significant technological and economic advantages, making these technologies more readily achievable than DACCS, they largely depend on the import of biomass. According to the Danish Climate Council, Denmark's biomass consumption is already higher than what is climatically justified and sustainable in the long term if we are to achieve the 110 % target without using DACCS.[2]



Implementation of DACCS seems inevitable if we are to meet the 110 % target while avoiding overuse of our biomass resources. Therefore, it is essential that the readily accessible negative emissions are exclusively used to compensate for residual emissions.

Consequently, a national carbon strategy should be developed to ensure that we avoid unintended consumption of biomass.

How much DACCS is needed in Denmark?

The path to achieving the 110 % target largely depends on how society as a whole, especially agriculture, transitions and reduces emissions. The Climate Council has previously outlined several possible scenarios for 2050, illustrating the need for negative emissions based on residual emissions and historical emissions. Figure 3 depicts the least optimistic scenario, where agriculture and land use still emit significant amounts of CO_2, with fewer energy-related emissions, and a net positive contribution from forests.[2]

In the scenario, an annual DACCS requirement of 5 Mton is presented to achieve net-zero emissions. Additionally, 8 Mton are needed to deliver the 10 % negative emissions compared to the 1990 level to achieve the 110 % target. At present, there is no plan outlined for how these 8 Mton will be realized. Furthermore, a scenario is explored where DACCS overall only needs to cover the 8 Mton of CO_2 required to achieve the 110 % target. But what does the landscape and energy balance look like for Denmark if we were to install between 8 and 13 Mton of DACCS capacity?

Estimated CO_2-equivalent greenhouse gas emissions in Denmak in 2050 [Mton]

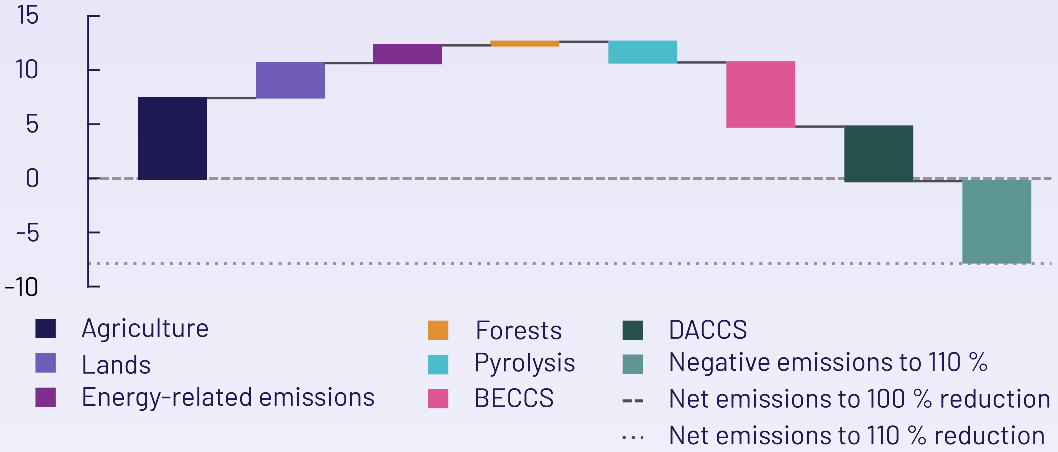


Figure 3: *Sector-specific CO_2-equivalent greenhouse gas emissions in the "Bio and CCS" scenario in 2050. Denmark's contribution to emissions related to international shipping and aviation is not included in the figure.*[2]

The DACCS technologies today

The DACCS technologies being developed today can vary significantly, but they all share the overall concept consisting of the four process steps illustrated in Figure 4.

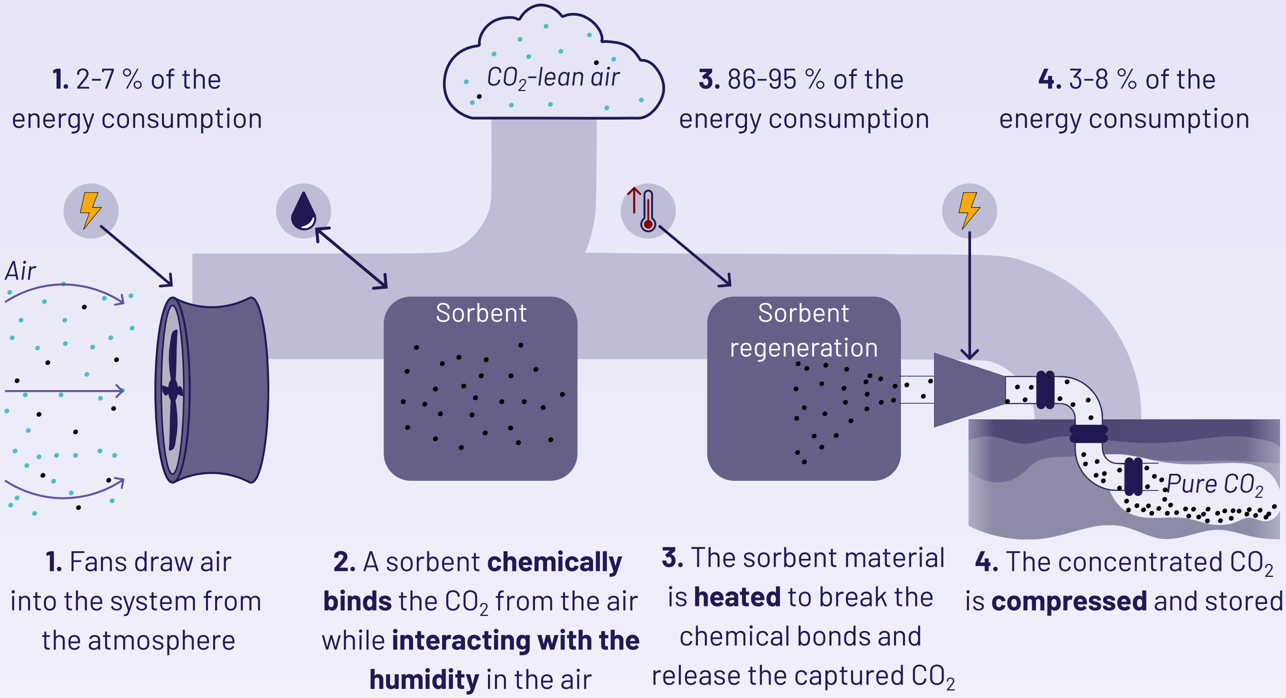


Figure 4: Overall DACCS process steps with estimated distribution of energy consumption in the process.

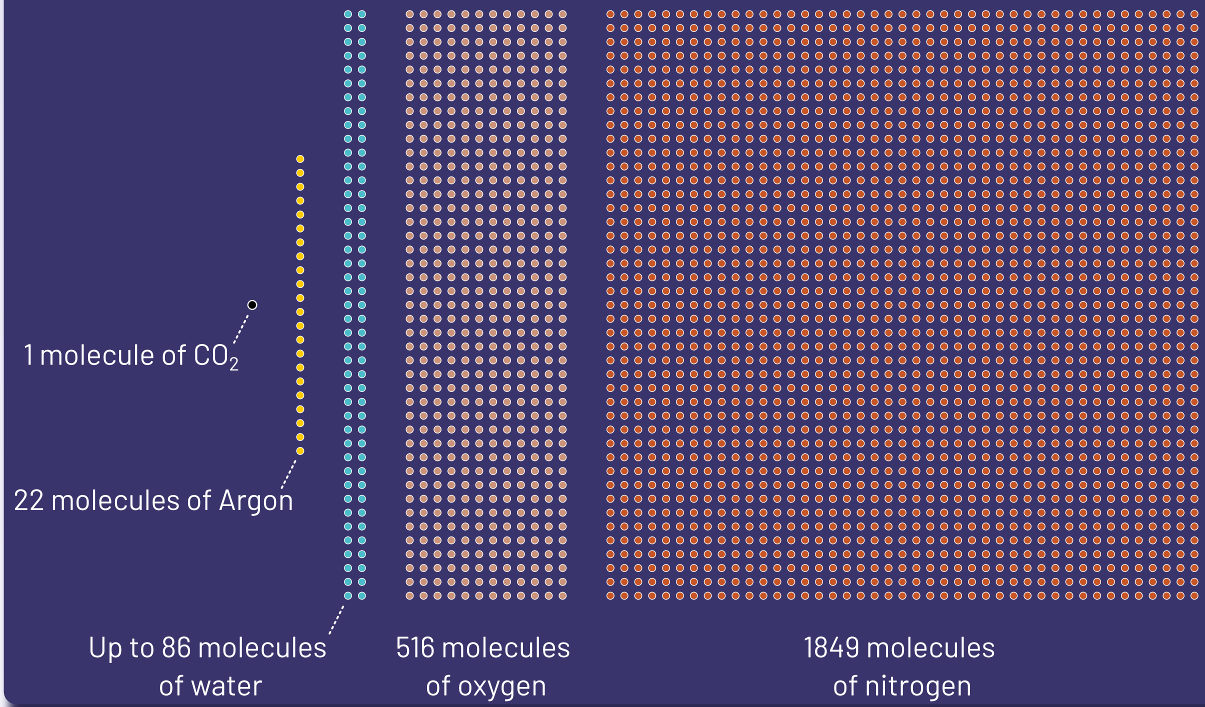
First and foremost, DACCS requires a large amount of air to come into contact with a sorbent. This sorbent chemically binds the CO_2, thus separating it from the air, which is then returned to the atmosphere. Although large amounts of CO_2 are emitted daily, the concentration in the atmosphere is so low that it is difficult and very energy-intensive to separate the CO_2 molecules from the rest of the molecules in the air. Once the sorbent has captured the CO_2, it needs to be regenerated so it can be used to capture more CO_2. This typically involves a process requiring a lot of heat at high temperature. The specific temperature depends on the technology and thus the type of sorbent used. The released CO_2 is compressed and can then be stored, for example, underground.

What is air?

Air primarily consists of nitrogen and oxygen, as illustrated in Figure 5. In fact, CO_2 only accounts for 420 ppm (parts per million) or 0.8 g per cubic meter of air. In other words, at least 1.25 million cubic meters of air need to be moved to capture just one ton of CO_2! Hence, DAC facilities resemble giant fans.

Another important factor is the water content in the air. On an average summer day in Denmark, as depicted in the figure below, the air contains 86 times as much water as CO_2. Regardless of the DAC technology implemented, the varying water content in the air will be in dynamic exchange with the DAC facility, causing either a net uptake or loss of water in the process.

Figure 5: *To find just one molecule of CO_2: the following amount of molecules must be processed.*



The leading DAC technologies

Today, two companies are leading in developing DAC technologies: Swiss Climeworks and Canadian Carbon Engineering. Table 1 provides key information about their two technologies adapted to a Danish context.

Table 1: *Key figures for the two most advanced DAC technologies. The numbers are based on modeling of the systems under Danish weather conditions by the authors of this white paper and have not been verified by the companies behind the technologies.*

	Climeworks (LTDAC)	Carbon Engineering (HTDAC)
Place of origin	Switzerland	Canada
Projects	15 in Europe	Pilot scale in Canada, demonstration coming in Texas
Capture method	Solid adsorption	Liquid absorption
Capture capacity	Modular, cyclic unit ~50 ton_{CO2}/year per unit	Continuous big scale unit, ~0.5-1 $Mton_{CO2}$/year
Heating source	Electric heating/ heat pumps	Natural gas with CCS/ electric heating
Process temperature [°C]	80 – 130 [4]	800 – 900 [4]
Energy consumption [GJ/ton_{CO2}]	3.8 – 9.5	5.5 – 8.8
Net water consumption [ton_{H2O}/ton_{CO2}]	-2 – 0	0.6 – 2.3
Estimated direct area usage [$m^2/ton_{CO2}/h$]	~10 500 [5]	~3 500 [5]
Estimated cost [USD/ton_{CO2}]	281 – 579 [6]	226 – 544 [6]

The two processes developed by Climeworks and Carbon Engineering respectively are chemically and process-wise very different. Carbon Engineering's technology, *high-temperature DAC* (HTDAC), see Figure 6, has the advantage of primarily relying on known technologies (cooling towers and calcination) that have already been proven to work on a large scale. This contributes to making the costs more predictable. The downside of the technology is that the energy consumption for CO_2 release is very high. This is because a large amount of energy is required to break the chemical bond. It also requires a high temperature of 800 to 900 °C.[4] Therefore, it is obvious to focus research on finding a sorbent that is less energy-intensive to regenerate and can be regenerated at lower temperatures.

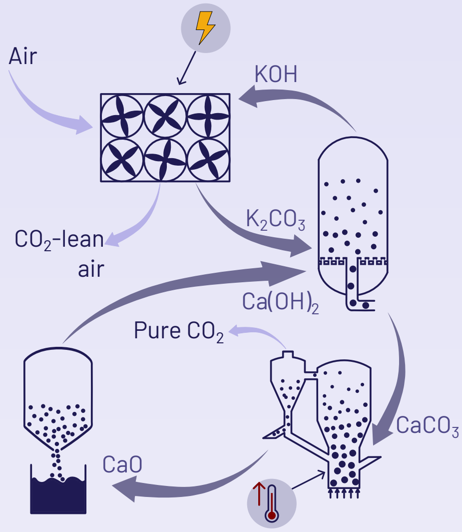


Figure 6: *Conceptualization of HTDAC.*[4]

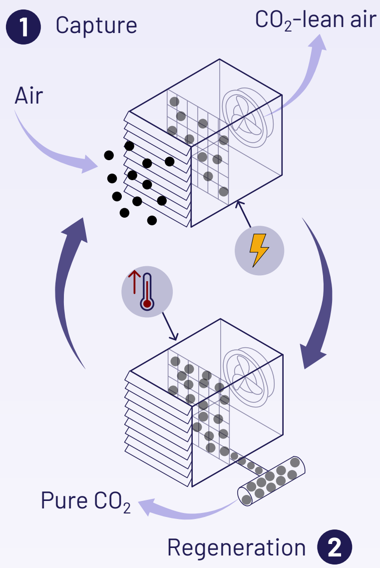


Figure 7: *Conceptualization of LTDAC.*[4]

Climeworks' technology, *low-temperature DAC* (LTDAC), shown in Figure 7, does not face the same issue with high temperature, as the desorption temperature is typically reported to be between 80 and 130 °C.[4] Efforts are particularly focused on finding materials that allow for a temperature at the lower end of the range. By lowering the temperature, excess heat from industry can potentially be utilized to drive the heating process. Additionally, heat pumps are often suggested as a heat source, as they are particularly energy-efficient. However, it should also be noted in this context that high-temperature heat pumps, at the scale required, cannot yet be considered a mature technology. Likewise, Climeworks' technology has not yet been demonstrated at large scale, and there is considerable doubt regarding the energy consumption and especially the speed of the process. All of these factors contribute to making the economic estimates uncertain.

Water consumption in DACCS facilities in Denmark

The humidity of the air plays a significant role in the water balance for DACCS processes. Processes that utilize an aqueous absorbent for CO_2 capture risk water evaporation into the atmosphere. Therefore, these processes are typically reported in the literature to have a significant water loss ranging between four and five ton per ton of captured CO_2.[4] However, this should be considered in light of the weather conditions, which have a considerable impact on the amount of water evaporating from the process. Under Danish weather conditions, the water requirement will vary between 0.6 and 2.3 ton per ton of CO_2 captured, depending on the season, as illustrated in Figure 8.

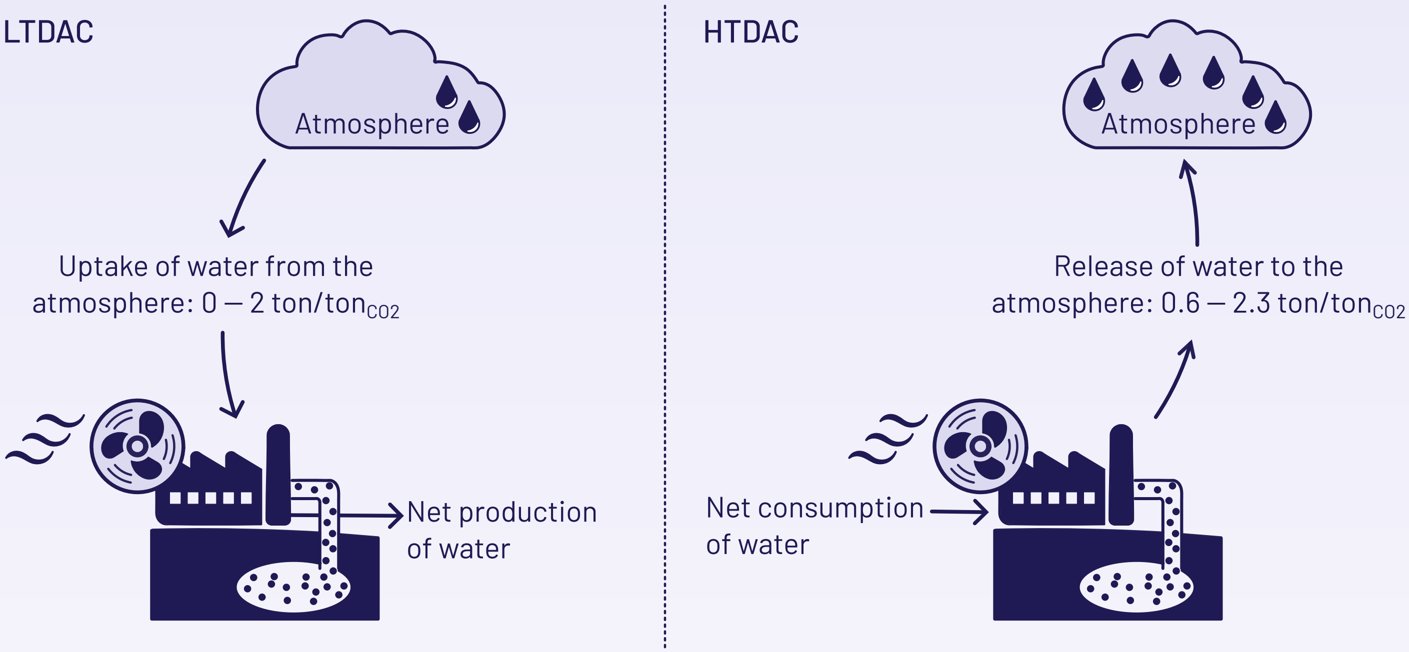


Figure 8: *Water balance in LTDAC og HTDAC.*

Processes utilizing solid sorbents face a different challenge. The adsorbent material used to capture the CO_2 will also capture some of the water present in the air. This makes the process significantly more energy-intensive because a considerable amount of energy is used to release the water as well. To be able to store the CO_2, the water must subsequently be condensed, making the process overall water-producing. Under Danish weather conditions, the process will, on average, produce around 1.5 ton of water per ton of captured CO_2. The production of water can be considered as an additional benefit of the technology.

A DACCS process that has a net water production is interesting for several reasons. Firstly, the water production contributes to the sustainability of the process as it does not rely on access to a freshwater source. Additionally, it highlights the potential to be coupled with power-to-X technologies, where clean water is a necessary input for the electrolysis process in the production of green hydrogen. For example, in the production of green methanol, 1.2 ton of water per ton of CO_2 converted to methanol are required. This means that in a Danish context, Climeworks' technology could contribute to making methanol production self-sufficient in both water and CO_2.

DACCS in the Danish energy system

Capturing 8-13 Mton of CO_2 through DACCS requires a large energy consumption, primarily due to the heating required for releasing the CO_2. The significant difference in process temperature between LTDAC and HTDAC determines which energy sources can realistically be utilized to operate the two technologies. For LTDAC, the heat can be supplied either purely electrically, electrically via a heat pump, or through, for example, surplus heat from industrial processes. To reach the high temperatures needed for HTDAC, combustion of a fuel is typically a requirement. The fuel could be natural gas or biogas.[4] However, recent research indicates that electric heating could also become a reality. Figure 9 illustrates the proportion of capture for both 8 and 13 Mton of CO_2 that would consume of the current consumption of electricity, surplus heat, natural gas, or biogas for the two types of DACCS.

The figure shows that if the heat demand for LTDAC is to be met via electricity, the development of a high-temperature heat pump is essential, as the electricity consumption can be reduced by more than 50 % compared to pure electric heating. It is also evident that industrial surplus heat is unrealistic as the primary energy source, as the available heat is significantly lower than the requirement. Although future power-to-X plants may increase the amount of surplus heat, it is not realistic that a significant portion of DACCS' needs can be met by this.

Looking instead at the perspectives in HTDAC, capturing 8-13 Mton of CO_2 will consume between 33 and 54 % of the current electricity consumption. Thus, the electricity consumption for HTDAC is slightly higher than the estimated consumption for LTDAC with heat pumps. If the heat is instead supplied through gas combustion, over 100 % of the current Danish biogas consumption or the majority of the natural gas consumption is required. It can be debated how realistic and appropriate it would be to use the scarce and valuable natural and biogas resources in this manner.

The Danish production of natural gas is expected to be phased out in the future due to a political desire to eliminate the use of natural gas. Biogas production, on the other hand, is expected to increase. The vast majority of this gas will likely be used for high-temperature processes in industry, as biogas is one of the few sustainable energy sources capable of delivering high temperatures through combustion.

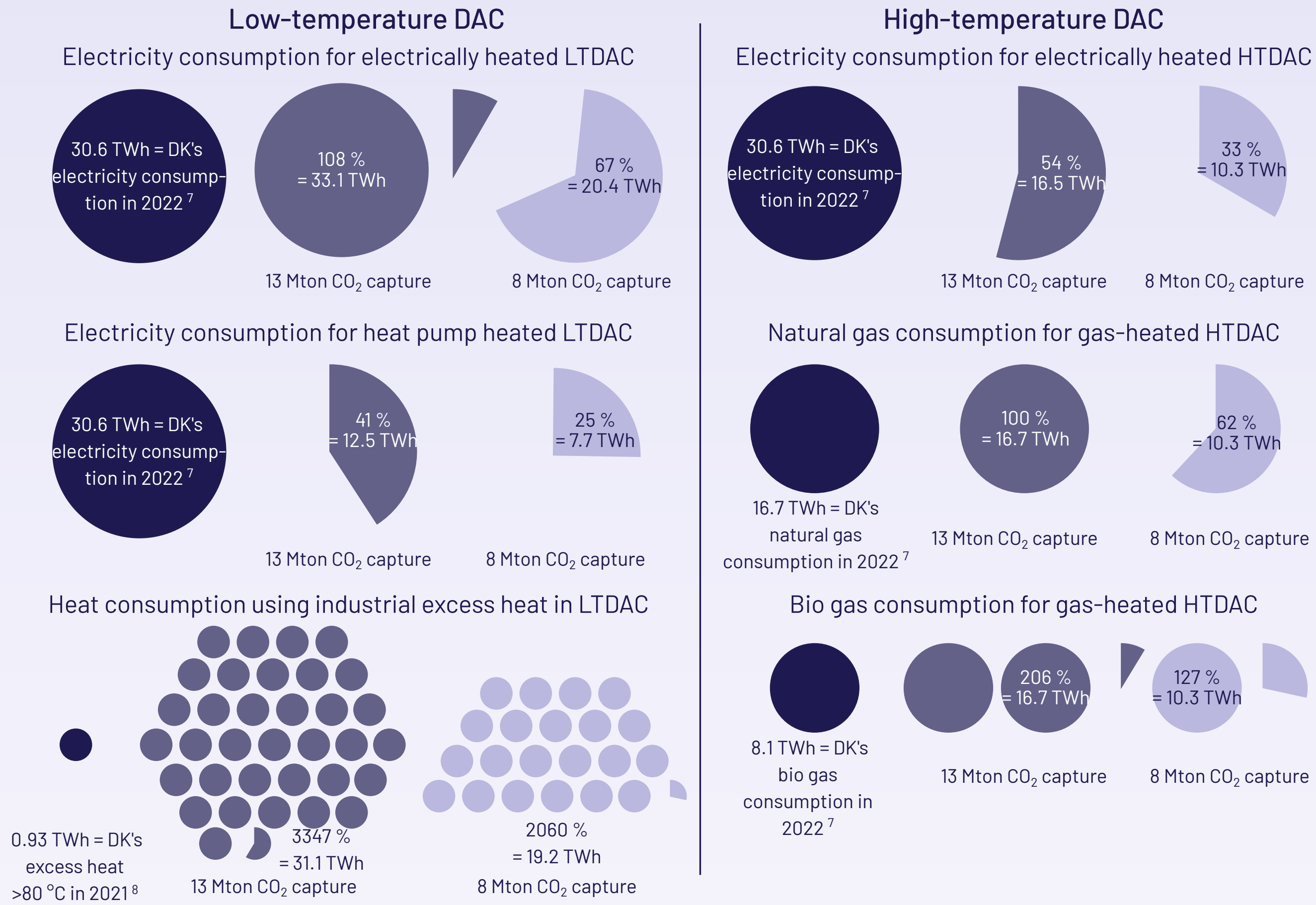


Figure 9: *Comparison of current production of electricity, natural gas, and biogas and the consumption for DACCS through capturing of 8 and 13 Mton CO_2 annually.*[7,8]

DACCS in the future energy system

To ensure a successful implementation of DACCS technologies in Denmark, it is essential to integrate the technology in a way that does not lead to increased indirect CO_2 emissions and that does not burden the future flexible energy system. Denmark's electricity comes from various energy sources throughout the year, primarily wind and solar, as well as electricity from natural gas, biomass, oil, and coal-fired power plants. Overall, Denmark's average carbon intensity in 2023 was 103 g_{CO2}/kWh.[9] However, there can be significant fluctuations, with hours having carbon intensities as low as 11 g_{CO2}/kWh, but also a few hours as high as 470 g_{CO2}/kWh.

Due to the indirect CO_2 emissions associated with using electricity for DACCS, the effective capture of CO_2 is less than the amount removed from the atmosphere. The overall capture efficiency of CO_2 is thus the ratio between the net amount of CO_2 captured and the gross amount captured in DACCS. This measure is crucial for determining the climate benefit DACCS can deliver.

In Figure 10, the total CO_2 capture efficiency is depicted as a function of the electricity consumption from DACCS and the carbon intensity of electricity. The figure indicates that with the average carbon intensity in Denmark in 2023, the overall capture efficiency, even with an electricity consumption of 10 GJ/ton_{CO2}, would exceed 70 %. Furthermore, the importance of green electricity production is illustrated, as there are very few hours each year with such high carbon intensity that, with the current electricity consumption of DACCS technologies, there would be a net emission of CO_2 from operating the plant if it is powered by electric heating.

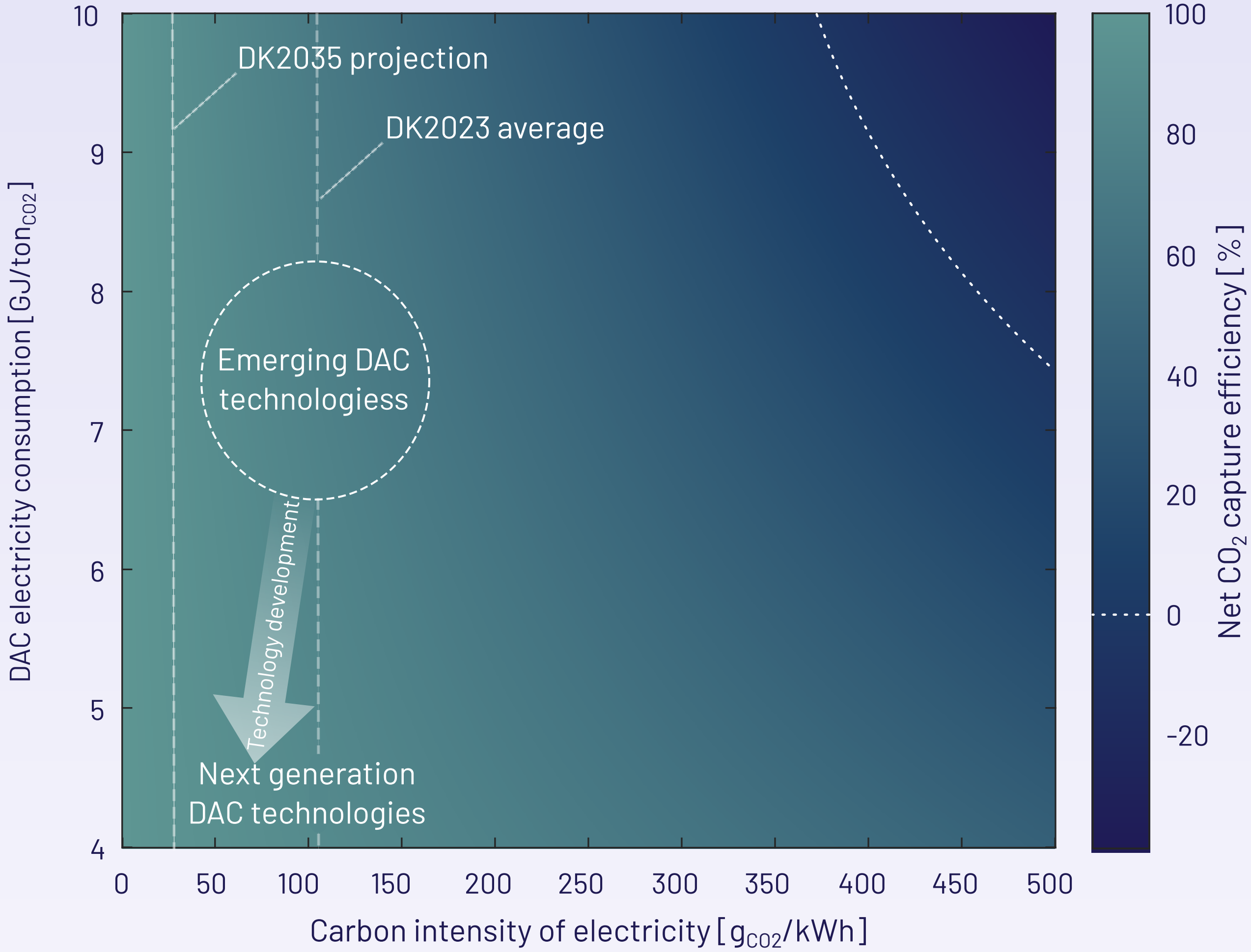


Figure 10: *Net CO_2 capture efficiency as a function of electricity consumption for DACCS and the carbon intensity of electricity from the grid.*

When DACCS is to be implemented in Denmark's future energy system, it will operate within an energy framework that encompasses electricity-demanding data centers, heat pumps, transportation, power-to-X facilities, and traditional electricity consumption as we know it today. Figure 11 depicts the estimated Danish electricity consumption in 2050 categorized accordingly. Additionally, the figure provides an estimate of the electricity consumption for DACCS to capture 8 — 13 Mton of CO_2. Of particular interest is the relationship between the projected consumption for power-to-X and DACCS, revealing that the capture of 8 — 13 Mton of CO_2 accounts for only about 14 % of the power-to-X consumption. Meanwhile, the electricity consumption for DACCS is comparable to that of data centers.

Thus, it is important that we ask ourselves the question: "How should the green electricity be prioritized?"

For example, could it be more desirable to prioritize a great climate impact by removing 1 Mton of CO_2 while producing some high-quality surplus heat rather than installing extra computing power with low-quality surplus heat? Or could it be more attractive for a waste incineration plant to operate a DAC facility with their electricity production and profit from negative emissions instead of selling electricity to the grid in a future where electricity prices are expected to be very low due to the renewable energy production?

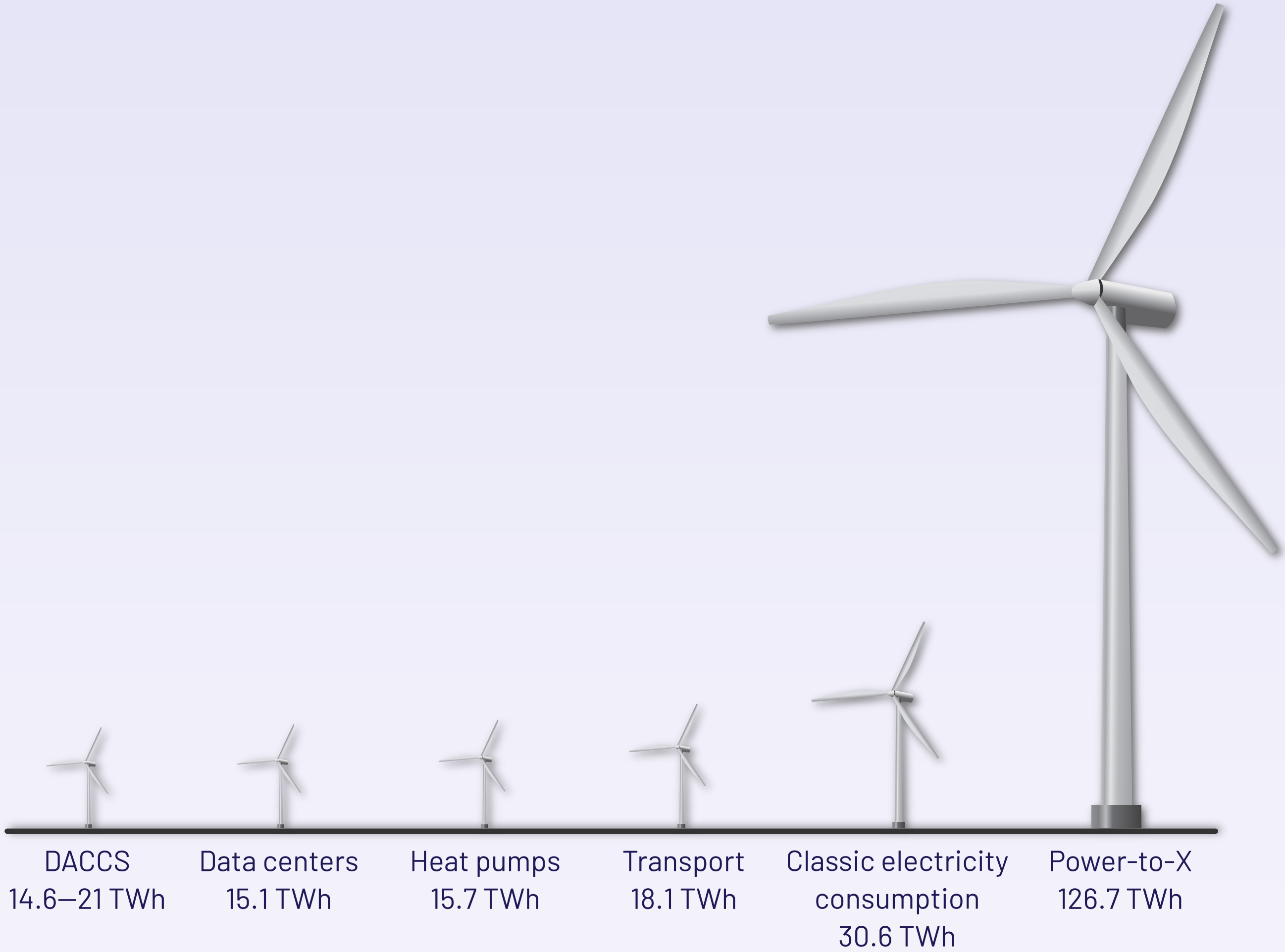


Figure 11: *Denmark's expected electricity consumption in 2050 divided into categories. DACCS is based on 8 — 13 Mton CO_2 capture.* [10]

Surplus process heat from DACCS

Both LTDAC and HTDAC have high energy requirements and generate a significant surplus of heat from the processes. This is primarily due to both processes involving cooling of the product gas and condensation of water. Figure 12 illustrates Denmark's unused surplus heat in 2021 in different temperature ranges. Additionally, the total surplus heat (after internal process integration) for LTDAC and HTDAC is included for the capture of both 8 and 13 Mton CO_2. The figure shows that both processes require extensive cooling, making it imperative to utilize this surplus heat for the sustainability of the technology. Therefore, we recommend that DACCS technologies are developed with a plan for how the surplus heat is utilized. This could be achieved, for example, by integrating DACCS with other technologies such as power-to-X or other industrial processes.

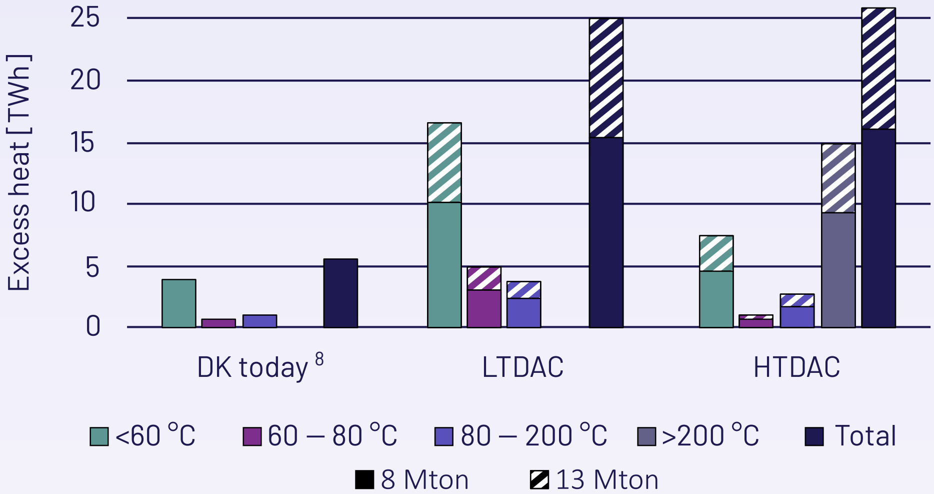


Figure 12: *Unutilized surplus heat in Denmark today*[8] *vs. the surplus heat for LT- and HTDAC for the capture of 8 and 13 Mton* CO_2 *indicated by solid and stribed fill, respectively.*

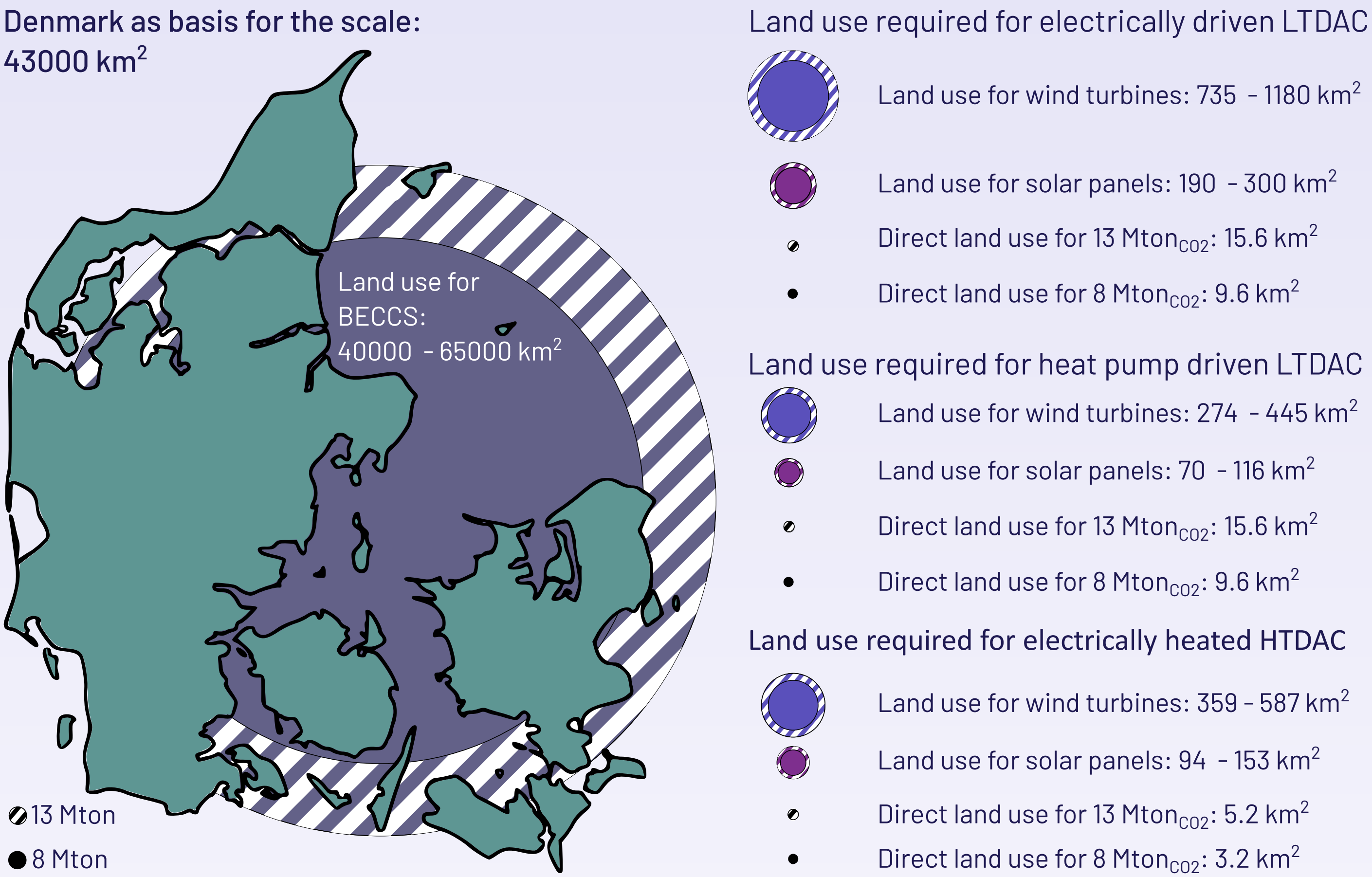
For LTDAC, the majority of the surplus heat is at temperatures below 60 °C. To utilize this low temperature, for instance in district heating, commercialization of efficient high-temperature heat pumps capable of increasing the temperature is necessary. In a future scenario where the surplus heat temperature can effectively be increased to the process temperature, around 50 % of the energy required for CO_2 release could be directly covered by the surplus heat.

For HTDAC, on the other hand, the majority of the surplus heat can be utilized at a significantly higher temperature. This makes the surplus heat more attractive and easier to allocate for other purposes. However, it is important to keep in mind that utilizing this high temperature places demands on the location of the facility, as long transport distances will result in significant heat losses.

The footprint of DACCS in the Danish landscape

With the implementation of DACCS in Denmark comes a pertinent question: *How much space does it occupy?* We have gained some experience with, for example, setting up wind turbines, and we know that there is significant resistance to large technical installations in the landscape. Figure 13 illustrates the land use for various methods of negative emissions, relative to the size of Denmark. The direct land use for capturing 8 and 13 Mton CO_2 via DACCS represents only a very small part of the total landscape. In contrast, the land use for renewable energy sources can occupy a relatively large area depending on whether the preferred energy source is based on wind or solar. However, it is worth noting that if CO_2 capture is based on BECCS, an area larger than the entire Denmark is required to capture 13 Mton per year by 2050.[11]

Although DACCS will occupy a considerably smaller area in the Danish landscape compared to BECCS, a direct land usage demand that could be 2 to 10 times larger than Sprogø is required, contingent upon the DACCS technology and the volume of CO_2 targeted for capture. One advantage of DACCS in this context is that the locations of the plants are highly flexible. Some of the most suitable locations for the plants include industrial areas, where surplus heat exchange can occur without long transport distances. In particular, co-location of power-to-X plants and DAC is interesting as they can exchange energy and water in addition to carbon. Another obvious location for DACCS plants is in connection with the CO_2 transmission network and the sites where CO_2 is to be pumped underground for storage. This will both minimize transportation costs and enable the placement of plants next to existing technical areas.



Figur 13: *Land use for various DACCS technologies including renewable energy sources based on electricity-based heating relative to the total area of Denmark.*[5] *Additionally, the land requirement for BECCS is depicted based on capturing an equivalent amount of* CO_2.[11]

Financial considerations

The current and future costs of DACCS are heavily debated. When discussing economics, it is important to agree on what constitutes the price. In this white paper, the cost of DACCS includes both the establishment and operation of the capture technology itself, compression and CO_2 transport, as well as storage. For several years, there has been a perception that the ultimate goal for DACCS is to reach a price of 100 USD/ton$_{CO2}$, equivalent to nearly 700 DKK – and that this is realistic. This has often led to optimistic and probably unrealistic cost estimates in the literature. A new study from ETH in Zurich provides a more realistic estimate of what the DACCS price can be reduced to when the technologies are implemented on a large scale.[6] A summary of the results of the study is shown in Figure 14.

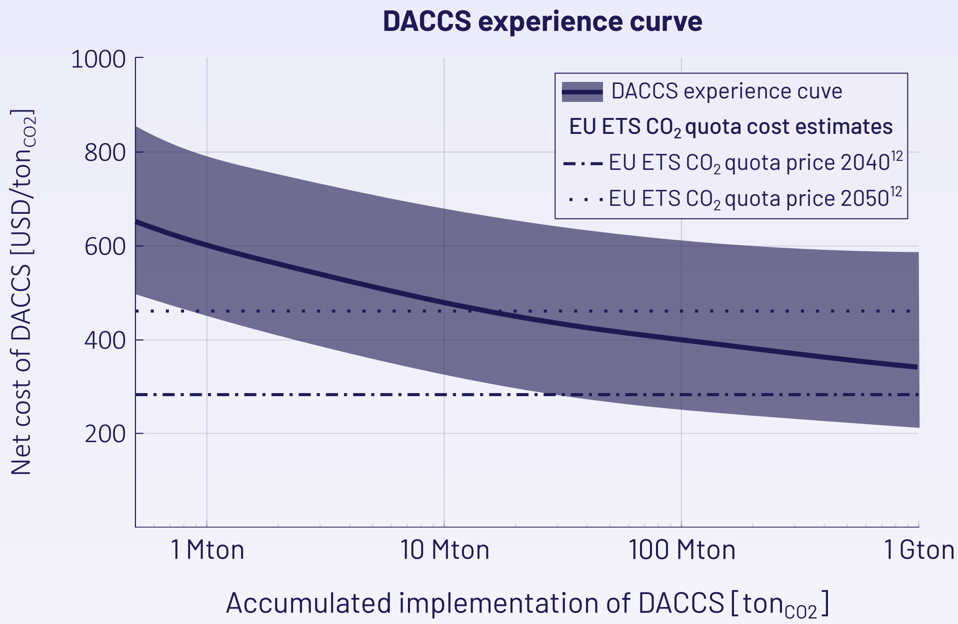


Figure 14: *Economic estimate for DACCS based on experience curves scaled up to capture 1 Gton CO_2.*[6]

The estimated costs for DACCS, when the technologies capture 1 Gton CO_2, are projected to be reduced to 374 and 341 USD/ton$_{CO2}$ for LTDAC and HTDAC, respectively, however with a relatively wide margin of error.

Although neither of the technologies immediately reaches a capture price that matches the goal of 100 USD/ton$_{CO2}$ (700 DKK/ton$_{CO2}$), the extrapolation shows that both technologies are competitive compared to cost estimates for CO_2 quotas in 2050 estimated in a study conducted at the Potsdam Institute for Climate Impact Research.[12] Additionally, the cost estimates are in the same order of magnitude as the support level in the NECCS pool, which is at 145 — 378 USD/ton$_{CO2}$.[13]

Financial co-benefits

When integrating DACCS into the Danish energy system, it is essential that the technology supports an energy system driven by fluctuating electricity production. In a Danish context, this means that DAC technologies should primarily be powered by electricity. In this regard, it should be investigated whether DACCS facilities can provide grid balancing services to the electricity grid. Grid balancing services are provided to balance an electricity grid where supply and demand for electricity do not automatically match due to changes in electricity production depending on factors like wind and solar conditions. The advantage of being able to enter the grid balancing market is that, in addition to contributing to an overall more reliable national electricity grid, the revenue of the process can be increased.

Another method to improve the business case for DACCS in the short term is to focus development on *direct air carbon capture and utilization* (DACCU). By integrating DAC with a process where CO_2 can be utilized for other purposes, the development of the capture technology itself is likely to mature as well. Currently, it is essential to prove DAC at a demonstration scale. This will provide technical experience and entail investment optimism. Since carbon is a finite resource, it is also unlikely in the long term to realize Denmark's power-to-X goals without using carbon captured via DAC.[14]

It is important to emphasize that DACCU does not deliver negative emissions like DACCS. Therefore, the recommendation for system integration with utilization processes should be viewed solely in light of the anticipated increase in investment willingness, which can benefit the development of DACCS technologies. In general, we recommend continuing the development of DACCS technologies that can operate symbiotically with other processes, focusing on the exchange of resources such as heat or water in addition to carbon.

Effective utilization of support schemes for negative emissions

Support schemes are necessary to promote the technologies and initiatives that can reduce CO_2 emissions and ensure a sustainable future. For example, Denmark's support schemes have previously achieved great success in the field of wind energy. Through targeted subsidies and political backing, we have developed a robust wind energy sector, leading to significant reductions in CO_2 emissions and establishing a global leadership position in wind technology. To ensure the effective use of support schemes for negative emissions, the priority should be on initiatives that guarantee long-term CO_2 storage with minimal risk of leakage.

It is crucial that support is provided to projects that would not be implemented without financing from carbon certificates and that ensure additionality. This means that the projects lead to real and new reductions in CO_2 emissions that would not have occurred without this support. To promote DACCS, incentive structures that support these technologies should be introduced. This includes establishing a specific grant pool for the development and demonstration of DAC technologies to accelerate their development and implementation.

Recommendations

Table 2: *Recommendations for various stakeholders to accelerate the advancement of DACCS.*

Technical recommendations 	Regulatory recommendations 	Market recommendations 
Demonstration of next-generation DAC technologies	***Development of a national carbon strategy***	***Introduction of incentive structures to promote DAC***
• Development of technologies with reduced energy consumption • Development of DAC processes that support an energy system with fluctuating electricity production • Design of DAC processes with co-benefits such as production of clean water, district heating, or grid balancing services • Development of processes that can be system-integrated with other technologies such as power-to-X	• Development of a comprehensive national carbon plan ensuring intended and sustainable use of biomass • Prioritizing support schemes for initiatives that would not be implemented without financing from carbon certificates and ensuring additionality • Directing support schemes to projects with long-term carbon storage and low risk of leakage	• Establishment of a grant pool specifically for the development of DAC technology, similar to the pyrolysis pool in 2022, to promote development and demonstration. • Launching a DAC pool on the scale of the NECCS pool in 2023.

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Research activities at AAU Energy

EUDP project: CHOCO$_2$LATE

The CHOCO2LATE project aims to develop and demonstrate a complete process chain for capturing CO_2 from the air, powered by solar energy, to produce liquid Fischer-Tropsch fuel. This project will focus on capturing CO_2 from the air by developing an innovative air scrubber and calcination technology.

Partners:
AAU Energy
TK Energy
COWI
Aqueous Solutions

Inno-CCUS project: eDAC

The project will provide guidelines for stakeholders across the entire value chain, covering both technological and societal aspects by assessing technology, economy, business models, and regulatory issues for DAC implementation in an electricity-based energy system. The project aims to ensure that DAC and DAC-PtX solutions are developed in a way that ensures successful integration and optimal implementation.

Partners:
AAU Energy
COWI
EuroWind
Port of Aalborg

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