Direct Air Capture (DAC) in Germany: resource implications of a possible rollout in 2045

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Direct Air Capture (DAC) is increasingly being discussed as a possibility to limit climate change. In this study, a possible rollout of the DAC technology at German coastal areas is analysed based on an existing climate neutrality scenario. For the year 2045 the resulting costs as well as land, water and energy consumption are examined. It is concluded that a realization of the DAC technology in Germany might be possible from a technical point of view. However, there is a high demand for land and energy. Since a rollout is needed to start in 20 years at the latest, the required discussion and evaluation should be initiated as quickly as possible.

DAC as a technology for enabling negative emissions

In efforts to limit global warming, negative emissions are seen as a necessary tool to achieve climate neutrality on the one hand and to compensate carbon dioxide (CO_2) emissions that have already been released to the atmosphere on the other. One technology for attain negative emissions is Direct Air Capture (DAC) that captures CO_2 from ambient air. By using DAC, gross negative and net negative emissions can be produced.

Gross negative emissions

Gross negative emissions fulfil the purpose of achieving a balanced CO_2 neutrality, e.g. for countries or companies. On the one hand, this could become necessary to compensate CO_2 emissions that cannot be avoided in any other way, such as those ones generated in agriculture. In this case, the CO_2 removed from the atmosphere by DAC (so-called DAC-CO_2) would have to be permanently stored underground (Direct Air Carbon Capture and Sequestration – DACCS). On the other hand, DAC-CO_2 could be used to replace fossil hydrocarbons, e.g. fossil fuels, by synthesizing DAC-CO_2 or CO (made out of DAC-CO_2) with green hydrogen and producing green fuels. The CO_2 released during its combustion, e.g., by road traffic, is considered climate-neutral, because it was previously removed from the atmosphere (Direct Air Carbon Capture and Utilization – DACCU).

Net negative emissions

Net negative emissions, on the other hand, describe emissions that are removed from the air and subsequently stored (DACCS) in addition to a country's or company's achievement of climate neutrality, thus lowering the atmospheric CO_2 concentration. Such net negative emissions have for a long time been called for by climate scientists as a necessary condition for achieving the 1.5°C target (IPCC, 2018). While the corresponding studies mostly focused on biomass with CCS (BECCS), DACCS is now also being discussed for enabling net negative emissions.

Direct air capture technologies

State of the art

DAC processes usually consist of three steps: First, the ambient air is directed to a sorbent, e.g. by using fans. Subsequently, the CO_2 from the ambient air must be bound by absorbing or adsorbing substances. Finally, the CO_2 has to be separated from the sorbent again by supplying thermal or electrical energy, so that the sorbent is again ready for a new cycle. The current processes and the companies implementing them can be summarized in two groups (Viebahn *et al.*, 2019).

In the *absorption and calcination process*, CO_2 is absorbed with potassium hydroxide (KOH) as an aqueous solution. The aqueous potassium carbonate

(K_2CO_3) resulting from the absorption is precipitated in a pellet reactor to form calcium carbonate ($CaCO_3$) and is decomposed into CO_2 and calcium oxide (CaO) by calcination. The latter is hydrated to calcium hydroxide ($Ca(OH)_2$) and is then available for further processing. Calcination requires very high temperatures (> 800°C), which the Canadian company Carbon Engineering (CE) achieves by burning natural gas, coupled with carbon capture and storage (CCS). This process can also be referred to $DAC_{highTemp}$. In addition to an existing demo plant in Canada, CE plans to bring into operation a commercial plant in 2022, removing 1 $MtCO_2$/year.

The Swiss company Climeworks and the US company Global Thermostat (GT) are working with *adsorption and desorption processes* (also referred to $DAC_{lowTemp}$). In this process, the CO_2 is first bound to a sorbent via organic chemical adsorption, which is then regenerated by low-temperature heat (approx. 100°C) or humidity under vacuum (temperature swing adsorption, TSA, in combination with pressure swing adsorption, PSA). The company Climeworks operates, mainly in Europe, over 15 demonstration plants. In September 2021, it commissioned a commercial plant "Orca" in Hellisheidi (Iceland) with a CO_2 removal capacity of 4 $ktCO_2$/year. The captured CO_2 is then injected into basalt formations where it carbonizes (becomes solid rock) within two years. GT operates several demo plants and a commercial plant with 4 $ktCO_2$/year in the US.

In addition, there are other smaller companies, some of them start-ups with their own developments. In total, plants with a cumulative capacity of more than 10 $ktCO_2$/year are currently being operated worldwide as demo or pilot plants.

Costs and resource consumption

Current *cost* assumptions for DAC are at 540 €/tCO_2, of which capital expenditures represent the largest share. By 2030, costs are expected to decrease to ~100 €/tCO_2 due to economies of scale, mass production, and technical learning (Viebahn *et al.*, 2019).

The *energy* required is composed of ~75 % heat and ~25 % electricity. Deutz and Bardow (2021) indicate an energy demand of Climeworks' demonstration plants, based on current measurements, of 700 kWhel/tCO_2 and 11.9 GJth/tCO_2. They state 500 kWhel/tCO_2 and 5.4 GJth/tCO_2 as Climeworks' target for 2030. In order to provide the required high-temperature heat, CE assumes a natural gas demand of 8.81 GJth/tCO_2 for its planned commercial plant, which includes electricity supply (366 kWhel/tCO_2) via using a gas turbine (Keith, 2018).

The *water intensity* of the processes depends on various factors such as temperature, ambient conditions, and solution molarity. CE reports net water losses due to evaporation for its pilot plant as 4.7 tH_2O/tCO_2. Climeworks' DAC-plants, on the other hand, produce between 0.8 and 2 tH_2O/tCO_2. The value can vary, depending on site conditions and sorbent selection (Viebahn *et al.*, 2019).

Current data for *land use requirements* are very imprecise. CE reports dimensions of 8 m x 200 m for capturing 0.1 $MtCO_2$/year (= 0.0016 $km^2/(MtCO_2\text{-year})$) in a conceptual design, but points out that the anticipated values refer only to the CO_2 absorption internals ("packings") and would significantly underestimate an actual plant size. Climeworks builds its plants in the format of a 40-foot shipping container. Real measurements of its plant in Hellisheidi show a land requirement of 0.26 $km^2/(MtCO_2\text{-year})$, that includes necessary installation areas and a centralized control unit (Deutz and Bardow, 2021). Considerably more space, however, is needed if the required heat is not provided as waste heat from other processes or via gas boilers, but has to be generated, for example, by electric heat pumps powered by photovoltaic systems.

Table 1 summarizes the described differences between $DAC_{highTemp}$ and $DAC_{lowTemp}$ plants. The key advantage of the $DAC_{lowTemp}$ process is that low temperature heat can be realized technically more easily. In addition, the integration of waste heat from electrolysers as well as from industrial or synthesis plants is possible. Another advantage is that the moisture contained in the air is available as water after passing through the process and does not have to be continuously supplied from outside, as is the case with $DAC_{highTemp}$. This enables the plants to be operated in regions where low-cost renewable energy is available but which are mostly arid regions. The small-scale modular design, as offered by Climeworks, also allows a demand-driven design as well as serial production.

	Unit	$DAC_{lowTemp}$	$DAC_{highTemp}$
Temperature level	°C	~100	~800
Design	-	modular	power plant unit
Electrical energy demand (year)	kWh_{el}/t_{CO2}	500 (2030)	366 (2025)
Thermal energy demand (year)	GJ_{th}/t_{CO2}	5.4 (2030)	5,25 (2025)
Water demand	t_{H2O}/t_{CO2}	-1	4.7
Direct land use	m^2/t_{CO2}	0.26	0.1
Cost development	€/t_{CO2}	< 100 (2030)	< 100 (2030)

Table 1: Comparison of high-temperature and low-temperature DAC systems – Source: According to Block (2021).

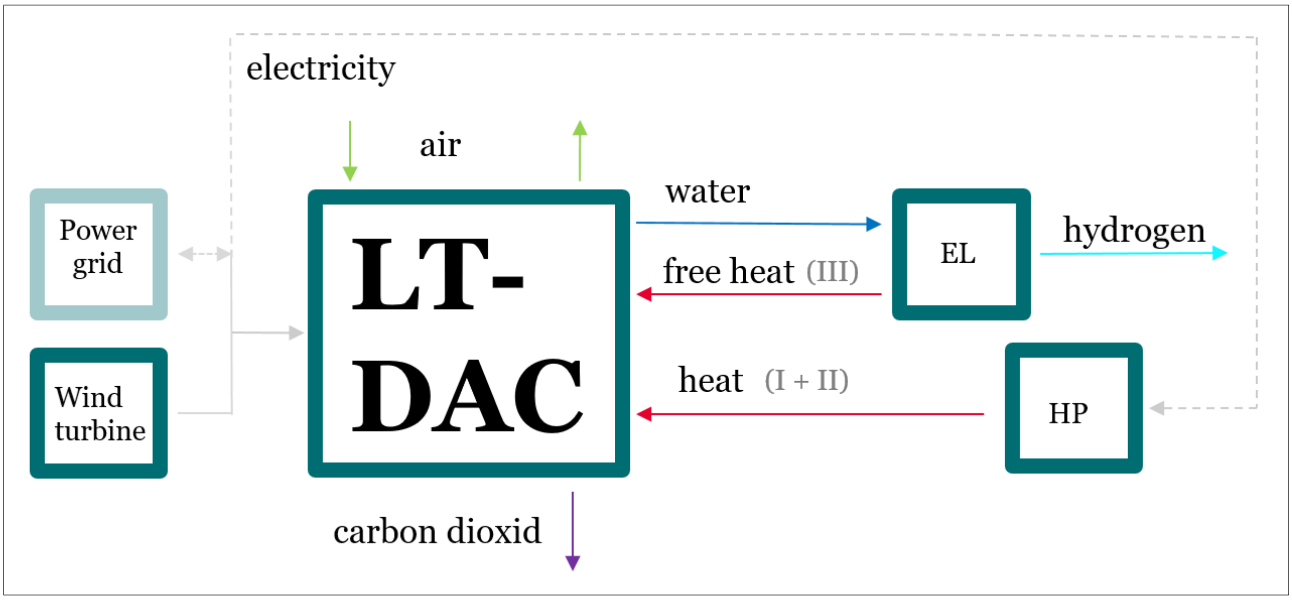

Figure 1: Schematic illustration of the three modelled cases (EL – electrolysis; HP – heat pump; LT – low temperature) – Source: According to Block, 2021.

Applying direct air capture in Germany

The KNDE scenario as a possible path to reach climate neutrality in Germany by 2045

In June 2021, the first integrated scenario showing a path towards a "Climate Neutral Germany 2045" (KNDE 2045) was provided (Prognos *et al.*, 2021). Shortly thereafter, the German government also adopted climate neutrality 2045 as a political goal. Using the common scenario method, the authors provided an economically viable strategy with which greenhouse gas emissions could be reduced through the implementation of appropriate measures in all sectors, from the energy sector to transport, industry and agriculture sector. In doing so, CO_2 emissions could be reduced by 65% to 438 Mt up to 2030 and by 95% to 65 Mt up to 2045, both compared to 1990 levels. The residue results in particular from agriculture, individual industrial sectors and waste management, whose emissions cannot be reduced further for various reasons. In order to achieve climate neutrality in 2045, the authors envisage gross negative emissions of 37 $MtCO_2$/year via BECCS and 20 $MtCO_2$/year via DACCS[1]. The allocation in BECCS and DACCS results from different model assumptions. Thus, for the first time, a consistent DAC implementation pathway for a country was provided, which is the basis for the following case study.

Design of possible DAC configurations

In order to both illustrate the dimensions of the required technology modules and determine the resource requirements resulting from the DACCS implementation pathway given above, different DAC configurations are modelled for the year 2045 (Block, 2021). According to the advantages given above, $DAC_{lowTemp}$ is used as a reference technology. Figure 1 shows the schematic layout of the technology modules. It is assumed that the DAC-plants will be installed near the German North Sea coast to be able to transport the captured CO_2 directly to possible CO_2 storage sites in the Norwegian North Sea. This setup avoids both onshore storage in Germany and transport from the hinterland to the coast. Three cases are distinguished for electricity and heat supply:

- Case I and II examine the use of onshore (I) and offshore (II) wind turbines for electricity production, combined with electric powered heat pumps;
- Case III analyses the possible energy savings from coupling DAC with electrolysers which could be installed on large platforms in the North Sea in the future[2], supplying them with water and using their waste heat.

The power supply for the DAC-plants is provided by the wind turbines, supplemented by provision of electricity from the grid. The electricity consumption for the electrolysers, however, is not considered here, since it would also occur without implementing DAC. Figure 1 schematically illustrates the systems layout of the three cases.

For simplicity, the analysis assumes that all plants will be installed in 2045. The following parameters, updated to 2045, are used for this purpose:

Direct Air Capture Unit

- Capture Capacity: 300 tCO_2/year
- Full load hours (FLH): 8,500 h
- Electric Power demand: 286 kWh/tCO_2
- Heat demand: 3.4 GJ/tCO_2
- Water production: 1 m^3/tCO_2

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[1] The 7 $MtCO_2$ still missing from the balance sheet will be achieved by crediting green polymers as feedstock in the chemical industry.

[2] See for example, https://www.northseawindpowerhub.eu/

Electric Heat Pump

- Coefficient of performance (COP): 2.85

Wind turbine

- Capacity: 3 MW
- FLH onshore: 3,536 h
- FLH offshore: 5,385 h

Electrolyser

- Type: Polymer electrolyte membrane (PEM) electrolysis
- Efficiency: 68%
- Waste heat supply potential: 14 GJth/tH$_2$
- Water consumption: 10 m3/tH$_2$

Results of the case studies

Table 2 shows the results of the three case studies. Key parameters are discussed below and benchmarked against the corresponding consumption figures of the city of Berlin (3.7 million inhabitants).

Electrical power: Locating DAC-plants at the North Sea coast has the advantage that both offshore and onshore wind energy can be used. The use of offshore wind turbines leads to higher full load hours and thus enables lower installed electrical power. Comparing the offshore wind power of 64 GW to be installed by 2045 as sketched in Prognos *et al.* (2021), about 3.6% of this load (= 2.29 GW) would be required in case II (using electric heat pumps). In contrary, heat coupling with electrolysers (case III) would lead to a reduction of the needed capacity to 1.06 GW.

Land use: Using onshore wind energy (case I) requires an area of 175 km^2 (1.165 turbines of 3 MW each), which corresponds to 20% of the area of Berlin. The space required for the processing plants (DAC, heat pump), in contrary, is small and amounts to only 3.4 km^2 (case I and II) and 2 km^2 (case III).

Electrical energy consumption amounts to 12.4 TWhel/year in the cases I and II (of which about 50% each for DAC processes and heat pumps) and 5.7 TWhel/year in case III (without heat pump), which corresponds to 97% and 45% of the electricity consumption of the city of Berlin, respectively.

Water: A quantity of 20 MtH$_2$O/year is provided by the DAC process. This corresponds to 9% of the drinking water demand of Berlin. At the same time, the DAC process, in interaction with the electrolysis process (case III), can not only cover the complete water demand, but also generate a surplus amounting to 0.085 m^3/tCO$_2$.

Cost: The cost of extracting 20 MtCO$_2$/year amounts to 1.5 and 1.8 bn EUR/year, in case the thermal energy is provided by heat pumps (cases I and II, respectively). By using "free waste heat" (case III), they cost is reduced to 1.3 bn EUR/year. This corresponds to CO$_2$ abatement costs of 75, 90 and 65 EUR/tCO$_2$, respectively.

Further potential need for DAC

The figures given above show that even a relatively small DAC capacity (capturing 20 MtCO$_2$/year) results in significant resource consumption. Much larger amounts of DAC, however, might be conceivable. Since the following options were not modelled within the KNDE 2045 scenario, they are only addressed qualitatively:

- In KNDE 2045, it was assumed that the remaining fossil fuels (apart from the use of electromobility) would be replaced by imported synthetic fuels. If these fuels were produced in Germany from green hydrogen and CO$_2$, an additional amount of 34 Mt of DAC-CO$_2$/year would be required.
- If the 37 MtCO$_2$/year of negative emissions, that KNDE 2045 assumes to be realised through BECCS, would not be available, this amount of CO$_2$ would also have to be implemented via DACCS (starting between 2030 and 2040).
- In aviation, only green kerosene is used in KNDE 2045 onwards. As the authors correctly write, CO$_2$

Year: 2045	Unit	Case I	Case II	Case III
Heat production unit	-	heat pump	heat pump	electrolysis
Installed heat capacity	GW	2.2	2.2	2.2
Heat demand	TWh/y	18.9	18.9	18.9
Power generation unit	-	onshore wind turbine	offshore wind turbine	offshore wind turbine
Installed power capacity	GW	3.5	2.3	1.1
Power demand	TWh/y	12.4	12.4	5.7
Installed number of wind power plants (3 MW)	-	1,165	764	355
CO_2-capture quantity	Mt/y	20.0	20.0	20.0
Installed number of DAC-plants (0.3 kt CO_2/y)	-	66,667	66,667	66,667
Land use for DAC plants	km^2	3.4	3.4	2.0
Land use for renewable energy plants	km^2	175	-	-
Water production	Mt/y	20.0	20.0	20 (net 1.7)
Total annual cost	Bn €/a	1.5	1.8	1.3

Table 2: Cumulative figures for the year 2045 – Source: According to Block (2021).

is only one cause of the greenhouse effect. At high altitudes also nitrogen oxides, black carbon particles, water steam etc. cause climate impacts. "In the context of a future, more comprehensive international climate protection regime, Germany would have to achieve correspondingly further negative emissions to offset the non-CO_2 effects of its international aviation" (Prognos *et al.*, 2021:90). Following this, further 43 Mt DAC-CO_2/year would have to be stored (calculated with a Radiative Forcing Index of 3).

- As mentioned at the beginning, also net-negative emissions will have to be enabled from 2050. Taking the "middle-of-the-road" scenario S4 (IPCC, 2018) as an example, globally 2, 5, and 10 Gt of net-negative emissions would have to be reached from 2050, 2060, and 2080, respectively. If Germany were to take on 1% of this amount (corresponding to its population share), further 20, 50, and 100 Mt of DAC-CO_2 would have to be stored from 2050, 2060, and 2080, respectively.

Conclusions

The results presented above raise a number of questions regarding their implementation. While DAC technology should be available in time after going through the usual learning and development processes, a rapid ramp-up of production will be required. Accordingly, sufficient production facilities will need to be available for mass production. Even if not the small plants used here, but plants of the "Orca type" (4 ktCO_2/year) or plants in a future order of 100 ktCO_2/year (Deutz and Bardow, 2021) are used, 5,000 or 200 plants would be needed in the reference case calculated above, respectively. Taking into account the possible demands of the four additional options and considering that the technology is not only needed in Germany but worldwide, a considerable production volume has to be assumed.

This study did not examine the use of high-temperature technology, such as that being developed by CE. In a climate-neutral energy system based on renewable energies, only hydrogen would be available for this purpose in Germany. Alternatively, waste heat from energy-intensive industry could be used and thus co-production could be established at existing industrial sites. So far, there is a lack of feasibility studies for this.

An essential factor for a timely implementation of the required strategies is the social acceptance. To date, discussion of negative emissions has taken place only in academics or NGOs. While the general public is rather slow to realize the need for a climate-neutral system, there is an urgent need for information regarding negative emissions. Sufficient acceptance will only be achieved through timely information and participatory development of possible implementation strategies.

Overall, given the large number of open questions, a comprehensive technology assessment from a wide range of perspectives and involving diverse stakeholders is needed. Since large-scale implementation will be needed in 20 years at the latest, corresponding studies and transformation strategies should be developed as soon as possible.

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