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Catching CO_2 from air?

A review of technologies for Direct air capture of CO_2 (DAC)

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About us

Vista Analyse is a social science consultancy with its main emphasis on economic research, policy analysis and advice, and evaluations. We carry out projects to the highest professional standards, with independence and integrity. Our key thematic areas include climate change, energy, transport, urban planning and welfare issues.

Our employees have high academic credentials and broad experience within consulting. When needed we utilise an extensive network of companies and resource persons nationally and internationally. The company is fully employee-owned.

Foreword

This report reviews the status of the technologies for Direct Air Capture of CO_2 (DAC). It includes both an overview over the technology development and costs. We also discuss the conditions that influence the localisation of such plants and assess the potential for DAC technologies in Norway. A short overview over technologies for removal of CO_2 from ocean and other natural waters – Indirect Ocean Capture (IOC) – is also provided.

The project has been carried out by a team of consultants from Vista Analyse and SINTEF: Filippo Bisotti, Anette Mathisen, Karl Anders Hoff and Jon Hovland from SINTEF, and Herman Ringdal and Orvika Rosnes from Vista Analyse. SINTEF has been responsible for the description and technical assessment of the technologies, while Vista Analyse has been responsible for the assessment of costs and economic potential of DAC.

The report was commissioned by the Norwegian Environment Agency. Henrik Gade has been our contact person in the Norwegian Environment Agency. We are grateful for discussions and comments to earlier drafts of the report.

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A.3 Cost breakthrough

1. Executive summary

The present report gives an overview over the status of technologies for Direct Air Capture of CO_2, DAC. We also discuss the conditions that affect the localisation of such plants and assess the potential for DAC technologies in Norway.

To capture CO_2 directly from air is a challenging task due to the low concentration of CO_2, 0.04% by volume. This is 100 to 500 times lower than the concentration in industrial flue gases where post combustion CO_2 capture is applied. This requires technologies for DAC to operate in a much lower rane region than other industrial scale CO_2 capture concepts and to enable treatment of large gas volumes per ton of CO_2 captured.

Two types of technologies for DAC

The DAC technologies under development today can broadly be classified according to **two dimensions**: carbon capture system (liquid solvent or solid adsorbent) and the temperature required for the regeneration of the sorbent (high or low).

The **liquid solvent-DAC** combined with high-temperature regeneration:
In this case CO_2 is first captured in an alkaline solution (KOH or NaOH) and then converted to solid calcium carbonate. The carbonate is treated at high temperature (higher than 850°C) to release nearly pure CO_2 gas which can then be liquified and purified before storage (or use). The DAC plant operates continuously, and it includes two nested chemical loops for the regeneration of the caustic solution and the release of the captured CO_2. Natural gas is typically used both for production of electricity (using a gas turbine) and for heating the calciner. Another possibility is to use electricity from the grid. In this case, the gas turbine is not needed, but natural gas is still necessary to obtain the high temperature heat for the calciner. In a longer perspective, also the calciner can be electrified or the calciner can be replaced by an alternative low temperature technology that can be used to desorb CO_2 from the KOH solution. Such low temperature options are, however, at a low TRL. Other options for a solvent-based DAC technology involve the use of amines as the reactive agent, similar to processes for CO_2 capture from flue gases.

The alternative to the liquid solvent technology (absorption) is the **adsorption process:**
A bed of solid particles is used as the agent to bind CO_2. Adsorption is a discontinuous process: first CO_2 is adsorbed from air and a desorption step follows to release concentrated CO_2. For desorption different technologies can be used. Vacuum, heating or a combination of these are the ones proposed in many cases, but other methods e.g. electro-swing is also being developed.

At present: Small-scale plants using solid adsorbent technology

The deployment of DAC is still limited. Currently, there are 18 small-scale DAC plants in operation worldwide, with a total capacity to remove only about 9000 ton CO_2 per year.

The largest existing plant is the Orca plant situated in Iceland that started operation in September 2021. This plant uses the **solid adsorbent** technology developed by the Swiss company **Climeworks**. The capacity of the Orca plant in Iceland is up to 4000 ton CO_2 per year. The location of the plant is, however, unique: the CO_2 is injected together with water into the basaltic rock beneath the plant, and the heat and electricity required to run the direct air capture process are supplied at low cost by the Hellisheidi Geothermal Power Plant.

Climeworks also started work on a new plant, Mammoth, adjacent to Orca, in summer 2022. This plant has a design capacity of 36 000 ton CO_2 per year when fully operational. However, even though the capacity is nine times larger than Orca's, this plant is still quite small.

Around the corner: Large-scale plants using liquid solvent technology

Another line of development is carried out by **Carbon Engineering** (Canada). Here, technology using **liquid solvent** combined with high-temperature regeneration is used. The technology of the high-temperature calciner equipment is not well-suited to small-scale modules. The minimum scale of this type of plant is at present in the range of 0.5-1 million ton CO_2 per year.

Occidental Petroleum and its subsidiary 1PointFive announced in October that they plan to begin detailed engineering and early site construction for their first large-scale DAC plant in Ector County, Texas, based on Carbon Engineering technology. Once operational in late 2024, the plant is expected to capture up to 0.5 million ton CO_2 per year, with the possibility to scale up to 1 million ton per year. The Norwegian company Carbon Removal plans a DAC plant using Carbon Engineering technology at the Energy Park in Øygarden municipality. They plan to capture 0.5 mill. ton of CO_2 per year, for permanent offshore storage by Northern Lights, with a possible expansion to 1 mill. ton.

Costs and further development

The DAC technology is still immature with high costs. The cost of carbon capture at the plant at Orca is currently 600 USD/ton CO_2 removed. Climeworks expects to reduce the costs to 300 USD/ton CO_2 by 2025 and 100 USD/ton CO_2 by 2030.[1,2] As this is a modular technology, the cost reduction is expected to be achieved through gradually scaling up the plants, mass production of air contactors and at the same time reducing costs by learning from experience.

As the technologies are still mostly in the testing phase, the costs are very uncertain. Our review of literature reveals large variation in estimated costs, both in the capital costs (CAPEX) and operational costs (OPEX) and energy used at the plants. Since there are currently only few small-scale pilot plants, it is not straightforward to estimate the scale-up from the first-of-a-kind to a n^{th}-of-a-kind plant. Once the CAPEX is reduced by technological development, the cost will to a large extent be determined by energy cost. A survey among experts carried out by Shayegh et al. (2021)[3] found the expected cost of capture to be in the range of 100 to 800 USD/ton CO_2 removed, confirming the large variation shown in the literature. The cost for a mature DAC technology will be very dependent on the energy cost. A cost of 100 USD can only be reached with low energy prices, under 0.05 USD/kWh.

According to our experience, at the current state, it is difficult to find a baseline estimate of the current DAC costs since (1) it is a novel technology and large-scale plant deployment is still limited and (2) publications on DAC are saturating the databases, thus, the flux of information incoherently mixes different sources and that makes it very difficult to compare the multitude of sources. It is necessary to have more technical information and learning from installed plants to get more robust and reliable TEA.

[1] https://www.nytimes.com/2019/02/12/magazine/climeworks-business-climate-change.html
[2] Noah McQueen et al 2021 Prog. Energy 3 032001
[3] Future Prospects of Direct Air Capture Technologies: Insights from an Expert Elicitation Survey, 2021, Front. Clim. 3:630893

Note that the costs given in this report do not include intermediate storage, transportation, or geological storage unless clearly specified. The IEAGHG report cited and quoted account for transport and storage.

What is important for choosing a site for DAC?

There are several aspects that are important when considering a site for a DAC plant: the cost and availability of energy, area, climate (air temperature and humidity) and what to do with the captured CO_2.

- DAC is an energy-intensive technology. The DAC plant can use electricity and/or natural gas, depending on the DAC technology. Hence, availability and cost of energy is important. As mentioned, the Orca plant in Iceland has a unique location, with close proximity to the heat and power plant.
- A large-scale DAC plant requires a large area of land. For instance, a liquid solvent type of plant with a CO_2 removal capacity of 0.5 million ton requires an area of 0.14 km^2 (about 20 soccer pitches). Moreover, the area should be free, so the intake of CO_2-rich air is not hindered, and the "used" air from one contactor is not taken up by another. Public perception of such a plant (fan noise, light) may also limit the number of suitable locations.
- How to dispose of the captured CO_2 is another important consideration. The captured CO_2 may be valuable and sold to other industries that use CO_2 (e.g., e-fuel for aviation). At large scale, and to obtain a climate positive effect the captured CO_2 must be stored somewhere. Hence, access either to a suitable storage site or to a transportation hub is important. If the DAC plant is situated close to a CO_2 injection hub, delivery of CO_2 by pipeline is a cheap option given long term commitment. If it must be transported, transport on ship is cheaper than road transport. About 1 million ton of CO_2 is needed for a cost-efficient ship transport. Hence, a location on the coast is preferrable. At present there is only one storage site being prepared, Northern Lights. However, several storage sites have been proposed and may be developed in the future. Having several sites will give flexibility and reduce transportation costs.
- Climatic conditions: At temperatures below zero a DAC plant can have operational problems. High humidity may also be challenging for operation. Snow and ice formation in and on equipment due to the huge volume of air that must be treated may reduce the operation time. An increase of start/stop operations of an industrial process always carry a risk. Plants in Northern Norway may be less efficient for this reason. At present, there is not enough information (i.e., industrial validation) to determine if there is a difference between the technologies with regard to cold climate.

Costs and Potential for DAC in Norway

We have considered the potential for DAC plants in Norway.

We study two hypothetical plants in Norway:

- **Case A** is a net 1 million ton CO_2 plant using a liquid process (Carbon Engineering-type). The plant is assumed to be located in Øygarden municipality, close to the Northern Lights CO_2 terminal. The plant can use either electricity or natural gas or combine the two, by using electricity for pumps and other equipment and natural gas for heating the calciner. (We use the latter case as our base case, but present costs for the other cases as well.) According to our understanding, the electricity that is necessary for a DAC plant of this size (0.5 million ton CO_2) is available without further expansion of the electricity grid. The captured CO_2 can be delivered by pipeline to Northern Lights.
- **Case B** is based on a net 100 000 ton CO_2 plant located near Mosjøen in Vefsn municipality. However, in order to compare the abatement costs of the technologies, case B is scaled for this purpose up to the same size as case A (mill. ton CO_2). In Case B it is assumed a process where CO_2 is adsorbed on a

solid sorbent (Climeworks-type). CO_2 is desorbed by applying a combination of temperature (90-100 °C) and vacuum. Released CO_2 gas can then be liquified and purified before storage. The energy for this process can be a mixture of electricity and waste heat: the desired temperature can be obtained by heat pumps driven by electricity, or alternatively, also the heat can be generated by electricity. Using waste heat will lower the cost, but such a plant can also be operated without waste heat available. There is at present no CO_2 storage near Mosjøen. CO_2 can be used on-site or transported to a hub for storage. At present, the cost of transportation to Øygarden will increase the total cost of DAC with storage significantly. A storage site off-shore Nordland County would reduce the transportation cost if coordinated with other CCS projects, as a small scale (such as 100 000 ton CO_2 per year) cannot justify the development of a geological storage.

The two technologies differ in scalability: the minimum size for the Case A-type is 0.5 mill. ton CO_2. Case B is selected to illustrate a different technology that offers the possibility of smaller scale plant. Case B also pinpoints the need for a certain total volume of CO_2 needed for a storage project. The costs here do not include intermediate storage, transportation or geological storage.

Figure 1 shows the abatement costs of the hypothetical **first of a kind plants** for each technology. Abatement costs are calculated according to The Norwegian Ministry of Climate and The Environment's guidelines for socio-economic abatement costs (*"samfunnsøkonomiske tiltakskostnader"*). Abatement costs for the hypothetical cases are 216 USD/ton CO_2 for the liquid based process plant in Case A (Carbon Engineering-type process), and approximately 385 USD/ton CO_2 for the adsorption process plants in Case B (Climeworks-type process), before transportation and storage are considered. With more optimistic assumptions for energy prices, operational costs, investment and capital expenses, the abatement cost may decrease towards 105 USD per ton of CO_2 captured for Case A, and 200 USD per ton of CO_2 for Case B. On the other side, with more pessimistic assumptions, the abatement cost per ton of CO_2 captured may increase to 315 USD for case A and 570 for Case B.

The advantage of the adsorption process plants is the possibility of downscaling it to a smaller plant, but this comes at a cost. For instance, the abatement costs of a plant with a capacity of 100 000 ton CO_2 are about 10 per cent higher than that of a plant with a capacity of 1 mill ton CO_2.

There is a lot of uncertainty associated with the estimated abatement costs for these hypothetical cases, and the costs should only be considered as an indication of future abatement costs of Norwegian DAC plants. Figure 1 shows the range for abatement costs for the two hypothetical cases for DAC plants, both for a first-of-a-kind and n^{th}-of-a-kind plant, with different assumptions. , Investment costs and capital expenses seem to be the most critical assumptions for abatement costs. This also implies that n^{th}-of-a-kind plants may be associated with significantly lower abatement costs.

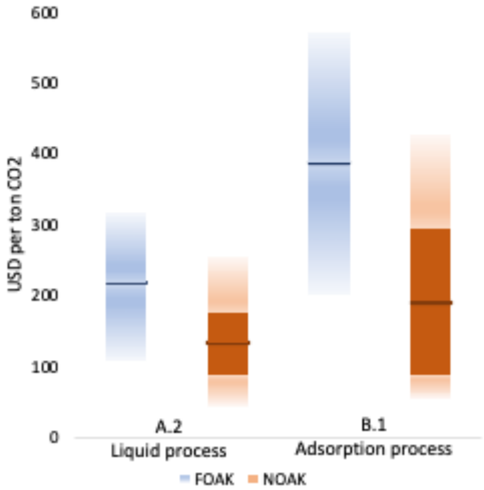


Figure 1 Range for abatement costs for hypothetical cases with different assumptions, for first of a kind (FOAK) and nth of a kind (NOAK) DAC plant, USD per ton of CO_2 captured.
Note: A.2 refers to the plant described above, using electricity from the grid and natural gas for the calciner. The costs for B.1 are calculated assuming 1 mill. ton CO_2; costs for a plant of 100 000 ton CO_2 are about 10 per cent higher.

Our estimated abatement cost of DAC is higher than current or historic prices of emission quotas in EU Emissions Trading System (EU ETS), and also higher than current CO_2-tax for Norwegian non-ETS industries. However, the Norwegian CO_2-tax is supposed to be increased for all non-ETS industries and reach 2000 NOK/ton (about 200 USD/ton at current exchange rate) by 2030. This is still lower than our estimate for the abatement cost of DAC, but only slightly lower than the abatement cost of case A.2.

Comparing the calculated abatement costs for the hypothetical DAC plants to other CCS-technologies considered in Norway reveals that the abatement costs associated with DAC are higher (the other CCS-technologies are in the range of 500-1500 NOK/ton CO_2, i.e., 50-150 USD/ton CO_2, see Klimakur 2030). The costs of DAC seem to be in the same range as the most expensive abatement measures analysed in Klimakur 2030.

We also estimate the required land and energy use to capture 15 mill tons CO_2 per year (almost 33% of the current annual Norwegian emissions), both with solid and liquid-DAC technologies. For the liquid-DAC solutions, three scenarios are proposed where the electrical and thermal energy supplies are satisfied with different sources: fully electric, natural gas based, and the hybrid case where the natural gas covers the thermal demand at high temperatures and the national grid the electrical energy. The natural gas and electricity consumptions are compared to the current natural gas export and the national electricity consumption. Depending on the technology chosen, the electricity use may be up to 63 TWh/y (approx. 40 % of production in 2021) and the natural gas used may be up to 3.3 % of the present export.

Barriers to DAC development

DAC may play a greater role in achieving the carbon-neutral society. As discussed above, the costs of removing CO_2 by DAC are higher than many other abatement measures considered in Norway, but not prohibitively high. DAC will also contribute to *net removal* of CO_2 and be a supplement to other methods to combat climate change. Other technologies, like CCS on flue gas and electrification, reduce emissions, but they are not net removal technologies.

At present, high capital costs, together with the uncertainty about how the technology will perform in “real life”, seems to be the largest concern. However, the main obstacle to large-scale development seems to be the lack a market for the "product" of the DAC plants – the CO_2 removed. Today, there is no market for the CO_2 removal credits: industries that are part of the EU ETS cannot use credits from a DAC plant at the EU ETS market; similarly, the non-ETS industries must still pay the CO_2 tax for their actual emissions, regardless of the CO_2 removal credits. Hence, nobody has any real incentive to buy the credits (other than for reporting in the companies' annual reports). Notably, there is some voluntary trade in the credits, and Climeworks has sold credits for 10 000 NOK/ton. However, the volumes are small.

By creating a market for the DAC credits, it is the market that "chooses" the future abatement technology, not the civil servants or the politicians. Investors must still take the investment decision and carry the risk of the investment. Hence, development of a market for DAC credits would be a better way to promote DAC technologies than subsidies or public investments.

DAC (and net removal technologies in general) is still an immature technology. Hence, supporting more research and testing that contribute to bringing down the costs would also be appropriate.

Further development of the technology

In addition to the two technologies discussed above that are at a TRL 7 to 9, there are several emerging technologies at TRL 6 or lower. These are discussed in the present report. As there is many groups working on DAC, both in academia and industry, variants of those at higher TRL or novel technologies may be proposed, developed and tested. The field is in continuing development.

Direct capture of CO_2 from seawater (Indirect Ocean Capture, IOC) has been proposed as a supplement to DAC. It is at a low TRL, 2 or possibly 3. Large volumes of water would need to be treated, with possible negative effect on marine life and biodiversity. While technically feasible in the laboratory, major development would be needed, if at all possible, based on technical, environmental and cost assessment.

List of abbreviations and acronyms

BECCS	Bio-Energy Carbon Capture Sequestration
BPM	BiPolar Membrane
BPMED	BiPolar Membrane ElectroDialysis
CAPEX	CAPital Expenses
CCS	Carbon Capture Sequestration
DAC	Direct Air Capture
DOC	Direct Ocean Capture
ESA	Electro-Swing Adsorption
ETS	Emission Trading System
FOAK	First-Of-A-Kind
GHG(s)	GreenHouse Gas(es)
Gt	Giga ton = 1 billion ton = 1 000 000 000 t
IEA	International Energy Agency
IEAGHG	International Energy Agency GreenHouse Gas [a branch of the IEA organization]
IOC	Indirect Ocean Capture
kt	Kilo ton = 1000 ton
LCOD	Levelized Cost Of DAC
L-DAC	DAC technologies using a liquid absorbent
(L)NG	(Liquefied) Natural Gas
Mt	Mega ton = 1million ton = 1 000 000 ton
NASEM	National Academy of Science, Engineering, and Medicine [also elsewhere abbreviated as NAS]
NET(s)	Negative Emission Technologies(s)
NOAK	N^{th}-Of-A-Kind
OPEX	OPerational EXpenses
S-DAC	DAC technologies using av solid adsorbent
T&S	Transport & Storage
TEA	TechnoEconomic Assessment
TRL	Technology Readiness Level
USD	US Dollar
VTS(A)	Vacuum Temperature Swing (Adsorption)

2. Introduction

The Norwegian Environment Agency has awarded SINTEF Industry together with Vista Analyse a project to review the status of technologies for capturing CO_2 directly from air (**D**irect **A**ir **C**apture, DAC).

To capture CO_2 directly from air is a challenging task due to the low concentration of CO_2, 0.04% (400 ppm) by volume. This is 100 to 500 times lower than the concentration in industrial flue gases where post-combustion CO_2 capture is applied. This requires technologies for DAC to operate in a different, and much lower concentration range than other industrial scale CO_2 capture concepts. Additionally, treatment of large gas volumes per ton of CO_2 captured must be enabled.

Scope

The scope of the project was given (in Norwegian), as follows:

Målene for dette oppdraget er at vi [Miljødirektoratet] skal få:

1. En oversikt over ulike teknologier for fangst av CO_2 fra omgivelsesluft, og over aktuell litteratur.
2. En bedre forståelse av hvilke faktorer som påvirker lokalisering av slik anlegg, og hva dette kan innebære for potensial og bruksområder for slike teknologier i Norge
3. Tiltaksbeskrivelser for minst to DAC-løsninger som vi kan bruke i våre klimatiltaksanalyser.

The target for the assignment is that the Norwegian Environment Agency will get:

1. An overview of the different technologies for capture of CO_2 from air, and relevant literature
2. A better understanding of the factors that affects the localisation of such plants, and what this means for the potential and range of use for such technology in Norway.
3. A description of at least two DAC-plants to be used in our analysis of measures to combat climate change.

Note that the costs given in this report do not include intermediate storage, transportation, or geological storage unless clearly specified. The IEAGHG report cited and quoted account for transport and storage.

3. Technologies including DAC business companies

Technologies classification

Direct Air Capture (DAC) is unquestionably one of the most prominent technologies to drive decarbonisation and emissions reduction at a level to cope with the Paris Agreement [1–7]. DAC paves the way towards net negative emissions. CO_2 capture from the atmosphere occurs according to two different technologies: liquid- and solid-based capture. This is the most common classification, and it groups the different technologies based on the sorbent.

The **liquid-based systems** rely on conventional absorption, while **solid-based** ones exploit adsorption, specifically vacuum temperature swing adsorption (VTSA) where the regeneration happens by slightly increasing the temperature and reducing the pressure to favour the desorption of the captured CO_2.

An additional classification distinguishes by means of the **regeneration routes**. There are the high-temperature (HT), low-temperature (LT), and LT steam or moisture-assisted swing adsorption. The latter class is not included in the present report due to a lack of publicly available data for the technology and any plans for pilot plants deployment. The following sections are focused on the DAC companies and research centres which are most active in the sector. We base our analysis on the readiness of the technology using published works and considering both planned and under-construction demonstrative pilot plants.

Carbon Engineering (Canada – liquid absorption)

Carbon Engineering is a Canadian company founded in 2009 by David Keith, professor at Harvard University. The company approach is based on solvent absorption and regeneration. Figure 2 depicts the plant configurations and the main equipment units (including compression to 150 bar) and Figure 3 reproduces the chemical loops involved in the DAC process. These figures also show some details on the operating conditions (Figure 2) and thermodynamic values for the different chemical steps and nested loops involved (Figure 3). The Carbon Engineering technology is a continuous process and has four major steps.

Referring to Figure 2, the air is fed to the contactor (crossflow pattern) where a liquid solution of potassium hydroxide (KOH) flows from the top to the bottom. The movement of the large volume of air is ensured by the fan ventilation system. The strongly basic environment favours CO_2 capture and a carbonate-rich solution leaves the unit. The exhaust caustic solution (enriched in potassium carbonates) enters the pellet reactor where it contacts with a caustic calcium solution, $Ca(OH)_2$. The caustic solution enhances the KOH regeneration while wet calcium carbonate ($CaCO_3$) is produced. The calcium carbonate decomposes at high temperatures ($T > 850°C$) in the calciner, where the heat is provided by burning natural gas in an oxyfuel chamber.

Thus, an air separation unit (ASU) is needed to supply the required amount of oxygen. Alternatively, Carbon Engineering is testing the possibility of substituting natural gas combustion with hydrogen from an electrolysis process [8,9]. The CO_2 produced from the heating of the calciner by natural gas is conveyed to the CO_2 purification and compression section. The calcium carbonate decomposition releases the captured CO_2 and leads to solid CaO which is the precursor of the caustic solution. The caustic solution is regenerated in the steam slaker tower. Indeed, in the steam slaker, the wet calcium carbonate is partially dried exploiting both the heat released by the exothermic reaction of the caustic solution production and the high enthalpic content of the streams leaving the calciner. The steam (recover from the slaker) is internally recirculated to hydrate the calcium oxide (CaO) to enhance the caustic solution regeneration.

A gas turbine covers the overall electrical energy demand. The flue gas exiting the gas turbine is treated in an absorption tower where most of the CO_2 is absorbed. To capture as much as possible the outlet from the absorber is mixed with the fresh air fed to the contactor. The flowsheet proposed by Keith et al. includes the natural gas used in the gas turbine and combustion in the calciner. This configuration leads to an overall CO_2 capture of 1.5 mill. t_{CO2}/y. Of this, 1 mill. t_{CO2}/y comes directly from the air and 0.5 mill. t_{CO2}/y is CO_2 from the natural gas used in the gas turbine and the calciner.

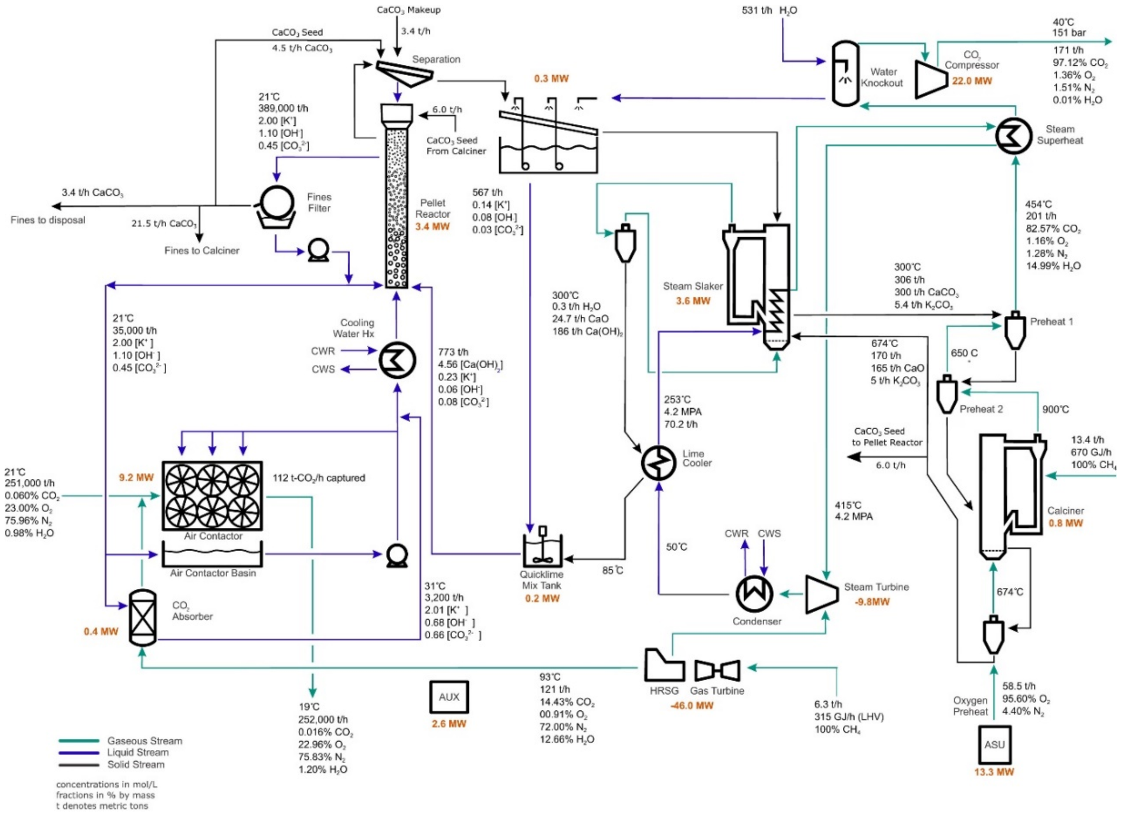


Figure 2 – Carbon Engineering plant (Picture reproduced from Keith et al., A Process for Capturing CO_2 the Atmosphere, Joule, volume 2, issue 8, 2018, https://doi.org/10.1016/j.joule.2018.05.006, under Creative Commons Attribution License CC BY-NC-ND)

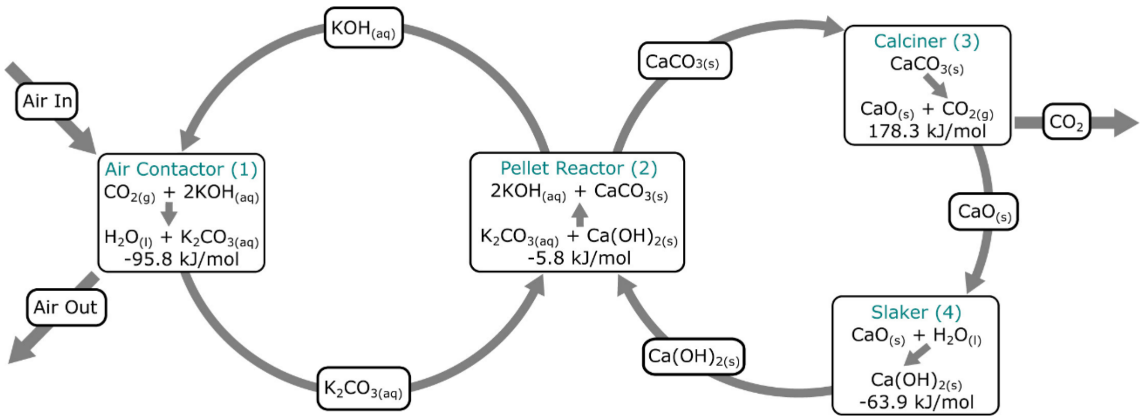


Figure 3 – Process chemical loops and corresponding thermodynamics (picture reproduced from Keith et al., A Process for Capturing CO_2 from the Atmosphere, Joule, 2(8), 2018, https://doi.org/10.1016/j.joule.2018.05.006, under Creative Commons Attribution License CC BY-NC-ND)

Climeworks (Switzerland – adsorption) and Global Thermostat (USA – adsorption)

Climeworks AG was born as an ETH Zurich spin-off and its ambition is to deploy solid-based DAC technology at prices by 200 USD/t_{CO2} by 2025 and below 100 USD/t_{CO2} by 2030 [10] (they have not announced whether they succeeded in 2022). Currently, Climeworks claims a CO_2 capture cost close to 600 USD/t_{CO2}. Climeworks has DAC plants in operation, in Switzerland (Hinwi) and Iceland (Orca, 4000 t/y). The technology relies on adsorption of CO_2 using special patented modules designed to minimize the pressure drop, and the adsorbent material have been developed to maximize the capture rate and CO_2 loading. Differently from the Carbon Engineering technology, Climeworks benefits of its modular approach, thus, the plant capacity scale up could be straight forward, but must be tested. Conversely, the costs reduction could not rely on the economy of scale as for the Carbon Engineering process but on economy of mass production.

The Climeworks DAC mechanism is relatively simple (Figure 4). The DAC vacuum temperature swing (VTS) process evolves into two steps: the loading phase (adsorption, phase 1) and the desorption (phase 2). The adsorption step occurs at ambient conditions and the air pass through an adsorbent material that selectively entrap the CO_2. Fans guarantee the air convection and the movement of large air volume through the module (i.e., overcoming the pressure drops). The adsorbent is a porous material functionalized with amines moieties to enhance the material affinity towards CO_2 (3-aminopropylmethyldiethoxysilan loaded onto nanofibers of cellulose) [11]. In this way is possible to chemically bind the CO_2 to the material instead of through a weak physical adsorption on the exposed surface.

The adsorption period lasts until the adsorbent is saturated. Then the module is heated up to 90-100°C. The thermal stability of the amine moiety limits the upper temperature. During the desorption process the pressure is lowered to around 50-60 mbar absolute pressure (i.e., 5-6 kPa) to promote the CO_2 desorption [12].

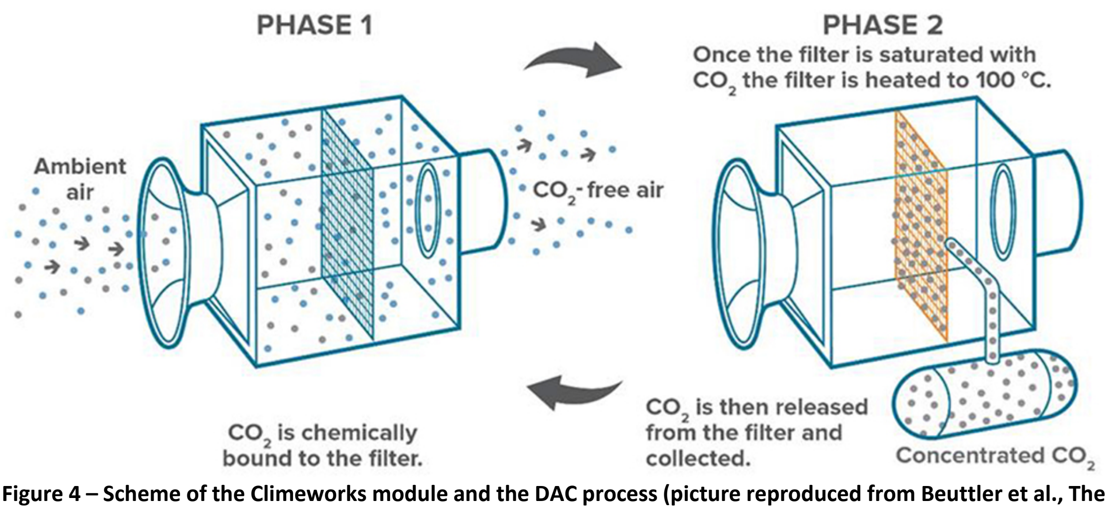


Figure 4 – Scheme of the Climeworks module and the DAC process (picture reproduced from Beuttler et al., The Role of Direct Air Capture in Mitigation of Anthropogenic Greenhouse Gas Emissions, 2019, Front. Clim. 1:10. doi: 10.3389/fclim.2019.00010 under Creative Commons Attribution License CC BY)

The Global Thermostat technology also relies on adsorption. According to the few and fragmented pieces of information available in the literature [13–15], their adsorbent is slightly different from the Climeworks. Their module contains an amine based chemical sorbent bonded to spongy honeycomb ceramic monoliths. Global Thermostat claims to have significantly reduced the energy requirement and the regeneration of the sorbent material takes place at 95°C.

GreenCap Solutions (Norwegian company – adsorption on zeolites)

GreenCap Solutions is a Norwegian company active in CO_2 capture from low CO_2 concentration flue gases and, currently, it is investing resources in its own patented DAC technology [16,17]. The GreenCap technology relies on the selective adsorption of CO_2 by zeolites [18,19][4]. Currently, GreenCap has two granted patents and three pending ones on DAC technology.

As Climeworks and Global Thermostat, the technology is modular. The DAC consumes only electrical energy during adsorbent regeneration. The main advantage of GreenCap technology lies in the adsorbent material features. The zeolite is commercial non-functionalized Al-Si material with a specific surface of 800 m^2/g. Since the material does not undergo any pre-treatment (such as functionalization) and its production is at industrial scale. The tested zeolites are claimed to achieve an almost complete depletion of the CO_2 from air (400 ppm at the inlet and 0.5 ppm at the outlet) and the pressure drops of the gas flow are limited to around 0.01–0.03 bar with a careful control of the velocity of the air. Both adsorption and desorption occur at ambient pressure.

The adsorbent bed superficial air velocity, the bed thickness, the bed size, and temperature are the main free variable to optimize the cycling capacity and the capture rate of the material. The adsorption takes place at ambient temperature (below 20°C) and for very high CO_2 concentration product down to -20 to -30°C. The adsorbent regeneration requires temperature range of 100-200°C and a hot CO_2 stream acts as sweep flow. The bottom and upper limits are fixed due to acceptable regeneration rate and acceptable material degradation. Temperature around 120–150°C are a trade-off between cycle production and material resilience as observed in existing pilot over 2 years operation.

The adsorbent lifetime is not known. The test on 300 t_{CO2}/y pilot facility revealed that the land use for the DAC facility is around 100-150 m^2. Modules can according to Greencap be easily and rapidly installed (the assembly takes 2-4 weeks). Since the solid-DAC technology is modular and the modules can be stacked, the land allocation for larger facilities (for instance, 300-400 000 t_{CO2}/y) proportionally increases up to 10-15 ha which correspond to 13-20 football pitches. As mentioned, the DAC technology is fully electricity-driven (heat pumps are used to achieve the desired amount of thermal heat for the regeneration) and at the current state the specific energy consumption is 1-1.5 kWh/kg_{CO2}.

A GreenCap challenge is to further reduce the energy requirement to 0.5 kWh/kg_{CO2}, depending on conditions. According to GreenCap, the main challenges towards a reduction in DAC costs are (1) energy integration to save electricity consumption, (2) minimize the entropy generation in the cooling and heating loops to reduce any inefficiency associated with the second thermodynamic principle, (3) the optimal design and integration of the heat pumps, (4) the air velocity and material surface to reduce the pressure drop and increase the adsorption rate of the zeolites, and (5) the reduction of the time required for the adsorption-desorption loops.

The electrical energy is mainly consumed in the heat pump and fans. The heat pumps are designed to cool down the air to enhance CO_2 adsorption while removing the humidity of the inlet air (water compete with CO_2 in the adsorption on the zeolite surface). Considering the heat pump's role, the optimal design of both the equipment and thermodynamic cycles should run all the steps involved in the DAC process as close as possible to reversible conditions. This aspect is quite challenging since the entropy waste reduce the efficiency of the process. Finally, the pilot testing (capture rate 300 t_{CO2}/y) demonstrated that the heat recovery for the cooling-heating loops requires large heat exchangers. The heat exchanger surface area needed at this scale is reported to be 100-150 m^2.

[4] SINTEF Industry (represented by Karl Anders Hoff, Jon Hovland, and Filippo Bisotti) and GreenCap (Jarle Skjæveland and Tor Christensen) had a video meeting to share information on the DAC technology on June 30th, 2022. The information here reported has been revised by the responsible from GreenCap to avoid sharing data and features on the DAC technology.

Verdox (USA – electro-swing reactive adsorption)

Verdox is a start-up from MIT (USA) whose aim is to develop a fully electricity-driven DAC. The process exploits the electro-swing adsorption (ESA), a particular process where a difference of voltage in a cell with electrodes enables the adsorption and desorption of a specific molecule [20]. Hatton (MIT) and collaborators found a novel device enabling the CO_2 capture from air and the release by applying a voltage of 1.2-1.5V to the electrodes [21–24]. The quinone material and the electrolytic cell is depicted in Figure 5. The cell comprises of two cathode electrode substrates coated with a CO_2-binding quinone-carbon nanotube (Q-CNT) composite sandwiching an anode electrode substrate coated with ferrocene-CNT (Fc-CNT) composite. A membrane separates the electrodes. The Fc-CNT serves as an electron source and sink in the loading phase (reduction) and unloading phase (oxidation), respectively, of the Q-CNT which is responsible for the CO_2 uptake and release. The electrodes are contacted with an ionic liquid which enables an effective ionic current to pass through the electrolyte and permits the diffusion of CO_2. Due to its configuration, the process is discontinuous and cyclical. The DAC evolves according two phases: firstly, the CO_2 is adsorbed into the porous material until saturation under 1.2V voltage to favour the chemical bound between the CO_2 and the adsorbent (loading) and then the desorption occurs thanks to voltage swing. The voltage swing provides the energy to reverse the CO_2-adsorbent reaction and disengage the entrapped CO_2 from the porous material. The reported values for the voltage refer to a single cell. The lab-scale validation shows that the faradaic efficiency of the process is high (> 90%) even after 7000 cycles.

The ESA process presents an additional advantage. Differently from temperature- and pressure- swing adsorption (namely, TSA and PSA), the sorbent capacity does not depend on Langmuir-type equilibria, thus, the uptake of CO_2 is independent of the concentration of the CO_2 in the feed. Verdox claims that its technology is flexible, and it can be easily integrated into any process in plug-and-play fashion due to its simple design and minimum requirement for auxiliary equipment. The energy consumption is estimated to be in the range of 100-150 kJ/mol_{CO2}. Hatton and collaborators claim that this value make the ESA technology competitive with Climeworks and Carbon Engineering DAC technology. Indeed, they estimated that the capture costs could range 50-100 USD/t_{CO2} [21], but this preliminary estimate is based on lab-scale data. "Normal" range of the energy consumption is reached after 5-6 cycles starting from completely new/unloaded cell. When the cell is new (never used before), it has the highest capture rate since the material is completely unloaded and it has its maximum storage capacity. Progressively, after some adsorption (loading) and desorption (unloading) cycles, the adsorbent reaches a stable operating condition and the cyclic energy becomes stationary. Based on lab-scale results, Verdox has started to design contactors based on 40 feet containers for absorption and a separate desorption module for a full scale DAC plant [23].

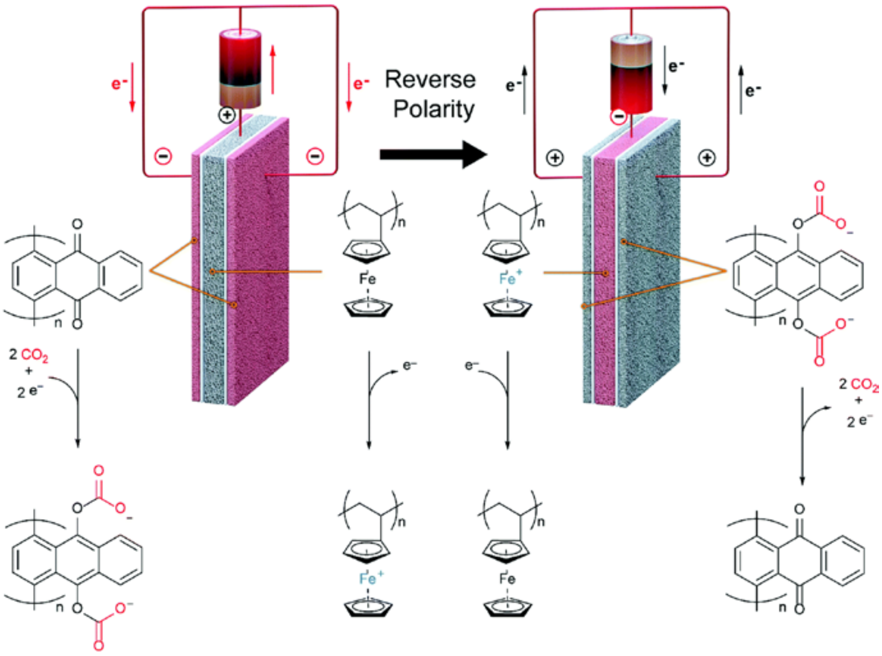


Figure 5 – Schematic of a single electro-swing adsorption electrochemical cell with porous electrodes and electrolyte separator (picture reproduced from Voskian and Hatton, Faradaic electro-swing reactive adsorption for CO2 capture, Energy Environ. Sci., 2019, 12, 3530 DOI: 10.1039/C9EE02412C under Creative Commons Attribution License CC BY-NC)

CSIRO (Australia – amino-acids salts solution washing)

CSIRO (Commonwealth Scientific and Industrial Research Organisation) is an Australian governmental agency for scientific research. Recently, the group lead by Paul Feron started its independent research on DAC using amino acid salts solutions washing [25,26]. The process configurations are shown in Figure 6. The liquid-DAC absorber exploits amino acid salts in aqueous solution. Due to low partial pressure of the CO_2 in air (i.e., 0.4 mbar = 0.04%) and the less basic environment compared to KOH solution as adopted by Carbon Engineering, the system requires a larger liquid flowrate.

Differently from conventional post-combustion capture, where, the overall rich solution is fed to a regeneration unit, most of the rich solution is recirculated directly to the absorber (> 95%), thus, only a small fraction of the solvent undergoes the regeneration. This process configuration avoids large energy consumption to regenerate the absorbent. Despite the amino acids-based DAC could appear ineffective due to less “basic” environment rather than caustic absorbent (KOH), it presents some main advantages: (1) the amino acids salts are well-known to have a potential for absorbing CO_2 with an effectiveness that matches that of MEA, and (2) the absorber is close to a conventional cooling tower for the cross flow pattern (well established unit), and this implies that the scale up may be straight forward and process development costs are reduced.

These statements confirm that CSIRO’s technology should already be at low-middle TRL (4) without any efforts or complications in the process development. The technology is already available for semi-industrial piloting, however, at the current state it is not clear whether CSIRO would license the technology. Beyond these considerations, the CSIRO experience can be considered as a benchmark for liquid-based DAC technologies since their techno-economical assessment is transparent and their levelized estimated cost of the captured CO_2 (around 650 USD/t_{CO2} and ranging from 400 to 1200 USD/t_{CO2}) is aligned with international independent scientific reports by IEA [6,7], American Physics Society (APS) [27], and National Academy of Science (NAS) proceedings [9,28].

In June 2022, Rolls-Royce exhibited an interest in the CSIRO technology and funded a research project for the pilot testing for 100 t_{CO2}/y [29,30] to be started during 2023.

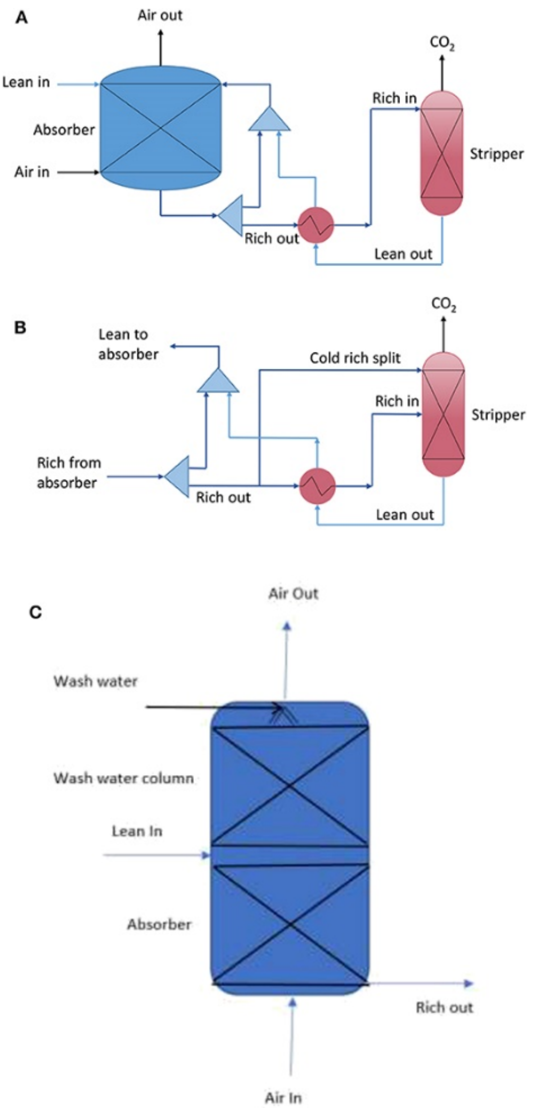


Figure 6 – CSIRO DAC technology and different possible process configurations (picture reproduced from Kiani et al., Techno-Economic Assessment for CO_2 Capture from Air Using a Conventional Liquid-Based Absorption Process., 2020, Front. Energy Res. 8:92. doi: 10.3389/fenrg.2020.00092 under Creative Commons Attribution License CC BY)

Kawasaki Heavy Industries (Japan - adsorption)

Kawasaki Heavy Industries is currently investing resources in a proprietary DAC solution [31,32]. The Kawasaki technology exploits CO_2 adsorption over a novel amine-impregnated porous material. There is no information about the support and the active-amine moieties properties due to intellectual property. According to the test they performed on small lab prototype (5-6 kg_{CO2}/day), the regeneration occurs at 60°C under vacuum conditions (20 kPa). The regeneration phase can utilise low-quality waste heat recovered through heat pumps due to the low temperature required during the desorption. Kawasaki tested the adsorption process under varying operating conditions (including humidity oscillations) and their experiments claimed to show a high stability and resilience of the adsorbent material. The technology is still under development and the technology readiness level is currently at 4-5[5] [33].

Bipolar Membrane Electrodialysis (BPMED) and Mission Zero Technologies (MZT, UK)

Sabatino et al. [34] developed a full scale DAC plant simulation and assessment for the first time using BPMED technology in 2020. In their first work they modelled the electrodialysis using lab-scale experimental data in previous work by Eisaman (TRL 1-2) to assess the economics of this novel technology. BPMED could allow for the complete electrification of DAC and potentially a complete decarbonisation of DAC if powered by renewables. Bipolar membranes enable to selectively transfer cation and anions to perform the solvent regeneration where the difference in the electro-chemical potential across the membrane drives the charge transfer.

The preliminary levelized cost of BPM-based process was 770 USD/t_{CO2} due to the high cost of the membrane (specifically, manufacturing, materials, and surface), the large electricity consumptions, and uncertainties on the lifetime of the materials [35]. More recently, they investigated the possibility for costs reductions in the future through experience, material performance, and electricity price reduction. The analysis is based on recent improvements in bipolar membrane material and performance. They demonstrated that the BPMED overall costs could drop to 250 USD/t_{CO2}, but the estimate is still high if compared to Carbon Engineering [34]. BPMED could appear expensive at the current state due to the uncertainties on the membrane materials and costs, these works provide a further attempt to (1) reduce the carbon footprint and impact of DAC and (2) mitigate the electrical energy demand for the solvent regeneration. Thanks to their activities, the authors showed an alternative to calcination and the process scheme looks more linear and simpler rather than the Carbon Engineering technology (Figure 7).

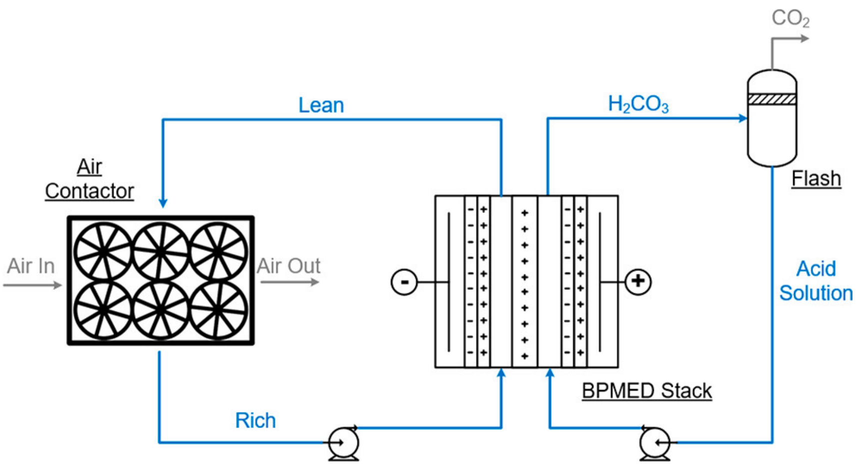


Figure 7 – BPMED process scheme (picture reproduced from Sabatino et al., Evaluation of a Direct Air Capture Process Combining Wet Scrubbing and Bipolar Membrane Electrodialysis, Ind. Eng. Chem. Res., 2020, 59(15), 7007–7020, under Creative Commons Attribution License CC BY-NC-ND)

The ion-selective membrane technology seems to be adopted also by Mission Zero Technology (MZT), an English DAC company. According to what advertised on the company webpage, their technology is still modular as Climework's, but continuous and not cyclic Their technology is said to be compact, modular,

[5] Full paper information available in GHGT-16 Lyon (24-27 October 2022) proceedings (not yet published)

electrically driven, and operates under ambient conditions. Moreover, MZT claims that their ion-selective membrane could drop the costs. Indeed, they claim the core process units (ion-selective separation) consume less than 800 kWh_{el}/t_{CO2} (2.8 GJ/t_{CO2}). According to MZT, the energy consumption drops thanks to some peculiar features of the electrochemical process and the adsorbent material they use in the technology. MZT showed that weak bonding of the CO_2 on the capturing material and the electrochemical separation consume 3-4 times less energy than existing thermal regeneration approaches. The process leverages existing, scaled, and mature technologies such as cooling towers and electrochemical water purification. MZT states that the core process units are off-the-shelf components, already produced in large volumes today [36]. In 2022, Mission Zero-led consortium won a 3.0 M£ government contract to pilot (120 t_{CO2}/y) DAC technology [37].

Other initiatives

Several start-ups propose their own technologies for DAC. Except for the cited main companies, there are a few additional initiatives which cover market niches or adopt similar technology with slight modifications.

Skytree [38] and Infinitree [39] are two start-ups in the field of DAC. Both are active in the market niche of urban farming. In addition, Skytree aims at providing the captured CO_2 to algal culture for biomass growth. Skytree is a Dutch spin-off from ESA (European Space Agency) funded in 2008 and the technology relies on electrostatic adsorption and moisturizing desorption at 80-90°C, thus, it is possible to fully integrate the system with heat pumps to recover waste heat sources. The moisturizing desorption looks similar to a steam-assisted desorption process where the competitive adsorption among CO_2 and water is tuned to facilitate the purge and, under suitable operating conditions, steam/humidity substitutes the adsorbed CO_2.

Infinitree is a more recent company (2014) whose core technology is based on moisture swing adsorption using ion-exchange resins with a tested capacity of 100 t_{CO2}/y so far. These two companies are the further proofs of the trend for the fully electrification of the DAC technology. Unfortunately, little information is available for both start-ups and more in general for the moisture driven electro-adsorption.

Hydrocell is a Finnish company founded in 1993 and collaborating with VTT research centre to develop a VTSA system for DAC [40–42]. There is a little information on the Hydrocell technology and performance. The DAC technology is a modular adsorbent system (standard shipping container) whose capture capacity is 1.3 t_{CO2}/y per unit/module. Anyhow, it is not clear the novelty in this DAC technology with respect to the Climeworks or Global Thermostat.

Susteon Inc. (USA) is developing its own DAC concept which is similar to Climeworks technology [43,44]. According to their claims, the MEA-impregnated adsorbent enables to reduce the energy demand for the material regeneration. The performance of the module is like the Global Thermostat (85°C using waste heat) and the cost for CO_2 captured is claimed to drop below 100 USD/t_{CO2}.

4. Techno-economic assessment (TEA) of DAC technologies

When dealing with DAC techno-economic assessment (TEA), it is important to distinguish between purely theoretical works and TEA provided by DAC companies or independent case studies. Purely theoretical studies focus their attention on the thermodynamics of DAC by integrating the potential costs reduction due to learning curve, technology deployment, and incentives. Conversely, DAC companies are interested in attracting funding, and therefore advertise their own patented technologies to attract public/private investments, thus, their estimates could be optimistic.

According to our experience, at the current state, it is difficult to find a baseline estimate of the current DAC costs since (1) it is a novel technology and large-scale plant deployment is still limited and (2) publications on DAC are saturating the databases, thus, the flux of information incoherently mixes different sources and that makes it very difficult to compare the multitude of sources. It is necessary to have more technical information and learning from installed plants to get more robust and reliable TEA. In addition, the shared details on the current patented DAC technologies are still relatively poor (i.e., limited access to capture rate, material performance; and assumptions adopted in TEA).

Anyhow, in-house TEA is still possible, whenever some information is disclosed, and comparing own results with published estimates. Despite the lack of details, many works try to project the DAC plant costs in the next fifty years, but there is not a tangible proof that these estimates could be realistic due to the recent oscillations of the energy market and of the price of the materials. To pursue the maximum level of transparency and objectiveness, the present paragraph will propose a full overview of the TEAs for DAC. The present section includes a review of both technical international report (IEA and other scientific society such US National Academy of Sciences and American Physical Society) and published works.

Thermodynamic considerations

DAC is a separation process where dilute CO_2 (400 ppm v/v = 0.04 %) is removed from the air and the produced CO_2-rich gas stream should contain almost pure CO_2 (at least 99%) after moisture/water removal. House et al. [28] compared the trend of the efficiency of several industrial process against the ratio of the final concentration (concentration of the product) with respect to the initial concentration (concentration in the feed before the separation/capture from an initial mixture). The statistic show that the lowest efficiencies are associated with process where the product is "extracted" and further concentrated from diluted sources. This is the case of capture of CO_2 from air (red dot in Figure 8). They show that according to statistics trend the DAC process is potentially full of inefficiencies [30,31] which reduce the overall process efficiency of DAC below 5%. In light of these observations, they justify that the DAC is located in the Sherwood plot[6] (Figure 8) where the purification/capture costs are close to 1000 USD/t_{CO2} (i.e., at least twenty times more expensive than conventional CCS technologies on flue gases). Also other works arrived at similar estimates adopting different approaches or reasonings [45–47].

[6] Sherwood chart plots the product initial concentration in the feed (x-axis) and the production costs related to its separation/capture (depending on the substance) and purification (y-axis). The lower the concentration in the feed stream the higher will be the costs associated with its separation/capture and purification. This is the general heuristic trend. The Sherwood plot is empirically validated over hundreds of chemical processes (metal separation, CCS, pharmaceutical, and other commodities production processes). It is remarkable that the Sherwood plot provides a preliminary rough estimate of the costs (i.e., the order of magnitude).

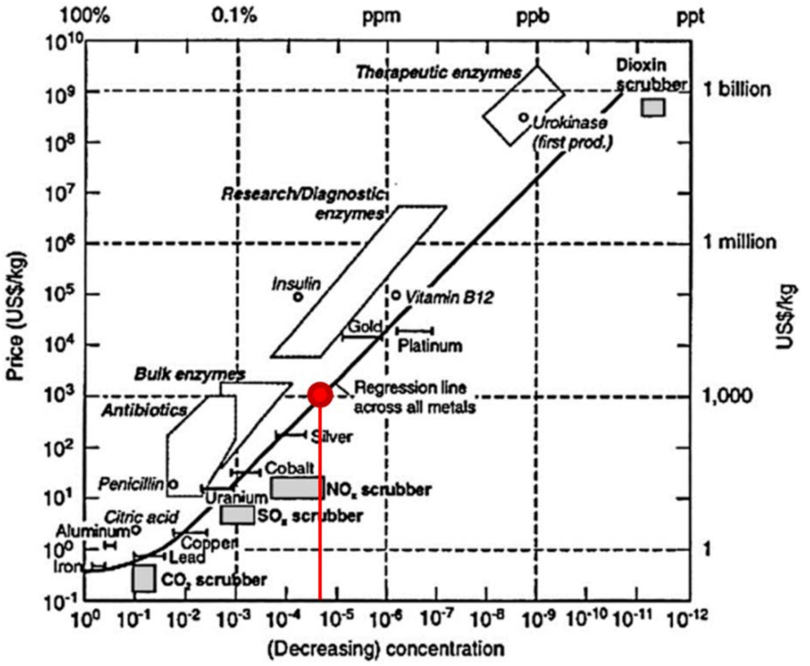


Figure 8 – A Sherwood plot showing the relationship between the concentration of a target material in a feed stream and the cost of removing the target material (picture reproduced from Grübler (1998), *Technology and Global Change*, Cambridge University Press, Copyright 1998, Cambridge University Press). The red dot represents the average composition of the air and the relative cost estimates using Sherwood plot as suggested in House et al. [28]

Literature review

Independent reports and works

This section reports the main outcomes looking into independent technical reports and the most relevant literature on DAC techno economic assessment (TEA). We would like to remark that no knowledge and comments of the CO_2 purity and other species composition are reported. Thus, we do not have any certainty that the produced CO_2 from the DAC processes fulfils the Northern Lights specification.

Review article by McQueen et al. (2021)

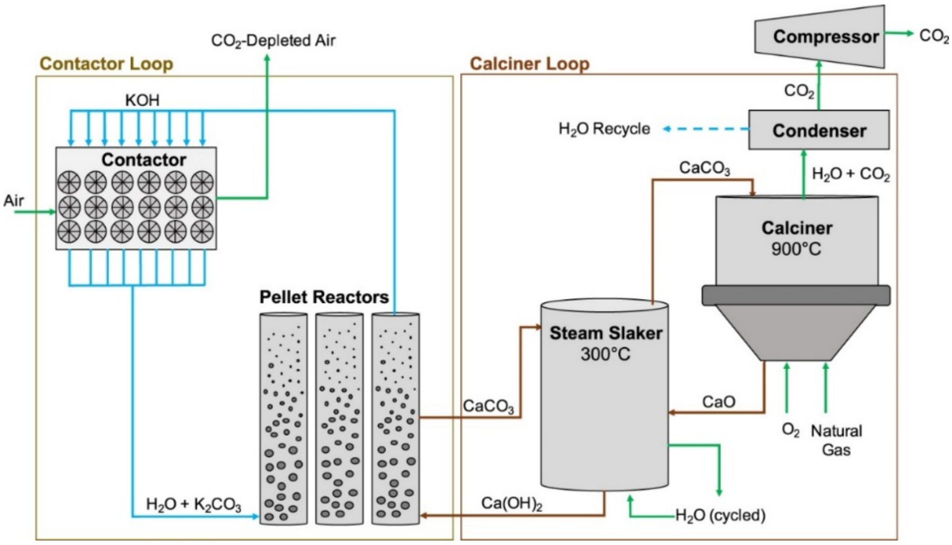
McQueen et al. published an exhaustive review comparing several TEAs available in the literature for both the Carbon Engineering (liquid based shown in Figure 9 top) and Climeworks (solid adsorbent module in Figure 9 bottom) [48]. Unfortunately, for the other DAC technologies reported in Section 3 - Technologies there are not any estimates from independent sources, only from the DAC company itself. Part of the present paragraph is directly coming from the cited article by McQueen et al., *A review of direct air capture (DAC): scaling up commercial technologies and innovating for the future*, 2021, Prog. Energy 3 032001 [48] reproduced under the Creatives Common Attribution CC BY 4.0 license for open access articles.

> *"DAC aims at selectively removing CO_2 from the atmosphere and the separation process is measured as flux of CO_2 from the atmosphere to absorbent/adsorbent material in the separation device per unit of time and contact area. The way in which CO_2 is effectively removed through air is through a chemical reaction with a base. The key is to maximize the number of interactions between the CO_2 coming in from air and the base chemistry present in the contactor. There are three key, high-level factors for the CO_2*

uptake in sorbent and solvent materials that must be optimized: (a) the basicity of the sorbent, (b) the loading of the sorbent onto a support structure, and (c) the exposed surface area of the sorbent".

Energy requirement and air contactor design

"Both the solid sorbent and liquid solvent DAC approaches require roughly 80% thermal energy and 20% electricity for operation [49]*. This is not an arbitrary percentage as both DAC approaches must optimize between a multitude of parameters. In both systems, the thermal energy demand results from the regeneration of the sorbent and the evolution of the previously bound CO_2 compounds. For the solid sorbent approach, the electricity requirements result from the contactor fans, which are required to overcome the system pressure drop, and the vacuum pumps, which remove residual air from the contactor during regeneration."*



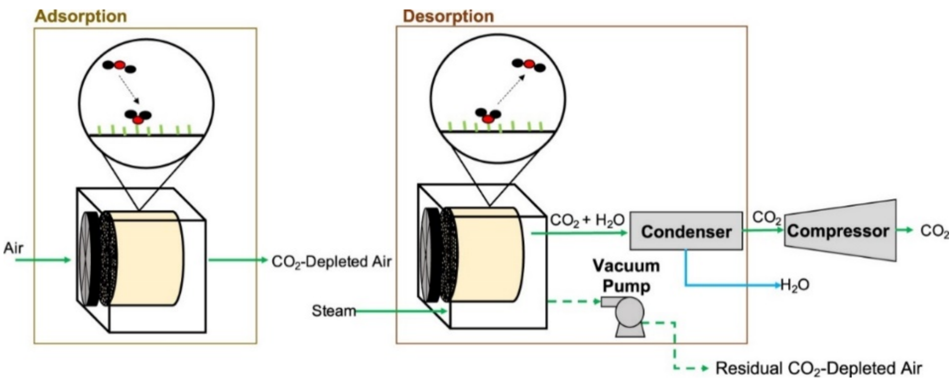


Figure 9 – Carbon Engineering (top) and Climeworks (bottom) technologies (picture reproduced from McQueen et al., A review of direct air capture (DAC): scaling up commercial technologies and innovating for the future, 2021, Prog. Energy 3 032001 under Creative Commons Attribution License CC BY 4.0)

"The liquid solvent system requires electricity for the contactor fans, also required to overcome the system pressure drop, as well as the pellet reactors, steam slaker and filtration units [8]. *Both approaches must optimize between the pressure drop across the contactor and the amount of CO_2 removed from the inlet air stream. "*

DAC companies propose different optimized solution. Carbon Engineering suggests huge void packed bed in cross flow configuration similar to cooling tower systems where the gas is forced to pass horizontally and the liquid flows from the top to the bottom [8]. Climeworks have inserted flat wash-coated plates inside the module. The configuration is reported in the patent [11], Sabatino et al. [50], and Mac Dowell et al. [51]. The air contactor resembles an air ventilation system, and the internal structured packing is designed to minimize the pressure drop. Global Thermostat adopts honeycomb monoliths where the high void fraction reduce the pressure drops without compromising mass and heat transfer [52]. More specifically, the sorbent DAC process has been reported to have thermal energy requirements near 6 GJ/t_{CO2} and electricity requirements at roughly 1.5 GJ/t_{CO2} [49,53].

"Overall, the energy demands of the solid sorbent and liquid solvent systems do not differ greatly from one another. However, the quality of thermal energy required for the DAC processes differs greatly. The solid sorbent system requires thermal energy on the order of 80–130°C, which may be met via industrial waste heat or other sources of lower quality thermal energy [53–56]. These temperatures are also well within the temperature range of commercial industrial heat pumps, which could upgrade lower-quality waste heat for this purpose [57]. The use of heat pumps requires additional electricity and reduces the thermal energy requirements, which increases the share of electricity in the DAC system beyond 20%. Because of the high coefficient of performance of heat pumps, this would substantially lower the electricity consumption compared to an approach using resistive heating. Conversely, the liquid solvent system requires heat near 900°C, which is required for the decomposition of $CaCO_3$ into CaO and CO_2 [17]."

Modularity and economy of scale

Most companies seem to make the contactors for the air in modules. This makes it easy to scale up by adding several contactor modules. However, there is little economy of scale in using many similar modules. There are benefits in mass production and that modules can be made in a dedicated plant and transported to the DAC site. Forty feet standard ISO containers have a well-developed handling system and logistic chain. High temperature processes using calcining of $CaCO_3$ need to have a certain size to be economic. Below a certain scale the calciner will not be cost-efficient. This is a major difference between the high-temperature and low-temperature processes.

On the other hand, a certain scale will be necessary to have an efficient logistics and transport chain of CO_2 from the DAC plant to the CO_2 injection/storage site. Preparation and cleaning of CO_2 before transport or use will have to be decided case by case. For transport by truck or ship liquefaction is needed. Typically, liquid CO_2 is stored at either 7 bar pressure and -50 C or 15 bar pressure and -28 C. At present in Norway, pipelines are only relevant for short distances. If several sources of CO_2 are close and can be transported by the same shipping route, e.g. a DAC plant and an industrial emitter of CO_2, the DAC plant can be of a smaller size. Smaller DAC plants may also be suitable if the CO_2 is to be used for some purpose locally. The CO2LOS projects optimizes ship transport and logistics and are supported by the Climit programme.

Materials requirement

Scaling up DAC will require expansion of regional and global supply chains. Both liquid solvent and solid sorbent DAC processes require large quantities of steel, other metals and concrete. It is worth mentioning that it is not straight forward to estimate the amount of material required for DAC facilities due to a limited amount of information and the lack of large infrastructure already in operation.

The liquid solvent process additionally requires chemicals and water both for plant start up and to make up for losses throughout the system. The solid sorbent process requires chemical sorbents to both initially fill the plant and the modules, as well as to replace sorbents that fall below the minimum effective CO_2 capture threshold after a given number of cycles. The sorbent lifetime is typically less than one year, which indicates that the sorbent will need to be repeatedly purchased throughout the lifetime of the plant [48,58,59]. Madhu [60] and Deutz [61] investigated the amount of materials (concrete and metals) used to build DAC facilities. Madhu et al. estimate that 1 Gt_{CO2}/y DAC plant requires from 17 to 36 mill. t of material (steel, concrete, copper, and aluminium) in case of liquid- and solid-DAC, respectively. The breakdown of the materials reveals that 4-6 mill. t/Gt_{CO2} of steel, 12-29 mill. t/Gt_{CO2} of concrete, 0.3-0.4 mill. t/Gt_{CO2} and 0.6 mill. t/Gt_{CO2} copper and aluminium are consumed, respectively. These values are well below the 1% (steel and concrete) and range 1-2% (copper and aluminium) of the current global production of these materials.

Review of the TEA from recent works on DAC

Table 1 and Table 2 gather the cost estimates for solid and liquid-DAC, respectively. As a matter of fact, looking at experts and independent studies only, the liquid DAC looks more expensive (126-560 USD/t_{CO2}) as stated by Keith, founder of the Carbon Engineering company [8,62] (94-232 USD/t_{CO2}). The NAS estimate is the only independent study which is close to the industrial values. It should be noted that the Carbon Engineering technology has not been validated on a large-scale yet. Despite the lack of industrial data, the TEA are based on previous quotations for similar equipment. The gap could be due to the different assumptions (optimistic for Carbon Engineering and pessimistic for the experts).

Conversely, the estimates by experts on solid-DAC are not aligned with the claims made by Climeworks. Climeworks states that from its experience on small-scale plants (Orca at 4000 t/y, for instance), the current cost per capture CO_2 is around 500-600 USD/t_{CO2}. However, the Swiss company is confident to drop this value below 300 USD/t_{CO2} and the target is below 100 USD/t_{CO2} through learning-by-doing [63,64]. These last values are aligned with current estimates from the experts. The progressive reduction of the capture CO_2 cost is more a consequence of the scale up, learning-by-doing rate, industrialization, deployment, and module/units production volume. This means that, while the capital investments (CAPEX) are lowering, the operative and maintenance costs (OPEX) become more relevant. This occurs in the overall projected costs estimates regardless the technology (solid- or liquid-based DAC). For this reason, the 100 USD/t_{CO2} target relies on cheap energy.

No independent study confirms and corroborates the estimates provided by Global Thermostat (cost around 50 – 80 USD/t_{CO2}) [52,65]. Nevertheless, some works are sceptical and criticize these numbers pointing out a lack of transparency in the claimed estimate [26,48]. The results for the energy consumptions and the economics (specific cost for CO_2 captured) gathered in Table 1 and Table 2 are in ligne with other references such as Sabatino et al. [50] (comparison of the optimized configurations of solid- and liquid-DAC plants) and Wijesiri et al. [10]. In the cited references the authors compared their estimates for adsorption DAC under different environmental conditions (varying humidity, for instance) showing that environmental conditions have an impact on the DAC performance.

Table 1 – Literature cost estimates for solid DAC (table reproduced from McQueen et al., A review of direct air capture (DAC): scaling up commercial technologies and innovating for the future, 2021, Prog. Energy 3 032001 under Creative Commons Attribution License CC BY 4.0). No knowledge of the CO_2 purity.

	Sinha et al[7] [66]	**Sinha and Realff**[8] [66]	**NASEM report**[9] [9]	**McQueen et al.**[10] [49]
Gross cost projection [USD/t_{CO2}]	–	86-221	88-229	Base case: 223 Geothermal: 205 Nuclear:233
Net removed cost Projection [USD/t_{CO2}]	–	–	124-407	–[10]
Scale [Mt_{CO2}/y]	–	1	1	0.1
Plant economic lifetime [years]	10	10	10	10
WACC[11]	–	–	0%	12.5%
Electricity resource (cost)	Unknown (-)	Unknown (0.06 USD/kWh)	Natural gas (60 USD/MWh)	US grid (0.06 USD/kWh)
Thermal energy resource (cost)	Steam (-)	Steam (0.0015 USD/kg)	Natural gas (3.25 USD/GJ)	Base case: steam (2.8 USD/GJ) Geothermal: waste heat (0.00 USD/GJ) Nuclear: slip steam (3.90 USD/GJ)
Sorbent material	MIL-101(Cr) Mmem-Mg2(dpbpdc)[12]	Material not specified	Material not specified	Material not specified

[7] There are two values used in this analysis, that correspond to two differing sorbents. The top values in this column correspond to sorbent material coated with two different mixed oxide frameworks (MOFs), namely MIL-101(Cr) and mmem-Mg_2(dpbpdc). MOF is the "active phases" in capture. This cost estimate only includes the associated sorbent energy requirements and costs, resulting in values of $75–142 per ton CO_2 for MIL-101(Cr) and $60–194 per ton CO_2 for mmem-Mg_2(dpbpdc). The research on this material stopped due to strong mass transfer limitations for CO_2.
[8] The values reported in this table represent the mid-range calculated values from the cited paper
[9] The costs and parameters reported in this table correspond to the mid-values (2-low through 4-high) presented in the NAS report for the case using natural gas for both electricity and thermal energy
[10] This analysis report costs for three scenarios: a base case using natural gas electricity and natural gas-derived steam for thermal energy, a geothermal case where the DAC facility replaces the condenser at the end of the geothermal cycle before reinjection, and a nuclear scenario where additional infrastructure is built to take a 5% thermal slip stream from nuclear. Additionally, the cost of the process is reported both without compression and including compression and transportation to end-use facilities. Since the compression conditions depend on the transportation method (pipeline, truck), and the transportation costs and emissions depend on the transit distance from the energy facility to the storage site, the base cost of the process has been reported from this analysis
[11] WACC (Weighted Average Cost of Capital) is the average rate that a company expects to pay to finance its assets
[12] This adsorbent has a stepped adsorption isotherm which poses challenges for the use in DAC processes on account of mass transfer rate limitations

	Sinha et al[7] [66]	**Sinha and Realff**[8] [66]	**NASEM report**[9] [9]	**McQueen et al.**[10] [49]
Sorbent lifetime (years)	–	0.5	0.5	1
Sorbent capacity (mol/kg)	2.9	2.9	2.9	2.9
Adsorption process	VTSA	VTSA	VTSA	VTSA
Cycle time for adsorption and desorption (min)	40 and 75	15-85	16, 28, 42	20
Desorption temperature (°C)	100	87	87	100
Desorption swing capacity (mol/mol)	–	0.8	0.8	0.8
CO2 compression included?	No	No	No	No

Table 2 - Literature cost estimates for liquid DAC (table reproduced from McQueen et al., A review of direct air capture (DAC): scaling up commercial technologies and innovating for the future, 2021, Prog. Energy 3 032001 under Creative Commons Attribution License CC BY 4.0)

	APS report [27]	**Mazzotti et al.** [67]	**Zeman** [68]	**Keith et al.** [8]	**NASEM report** [9]
Gross cost projection [USD/t_{CO2}]	480-610	376-428[13]	303-444	–	147-264[14]
Net removed cost projection [USD/t_{CO2}]	610-780	518-712[13]	309-580[15]	126-232[16]	199-357[14]
Scale [Mt_{CO2}/y]	1.0	1.0	1.0	1.0	1.0
Plant economic lifetime [years]	20	20	20	25	30
WACC	10.3%	10.3%	10.3%	5.5% and 11.7%	11.5%
Lang factor	4.5-6[17]	4.5	4.5	3.2[18]	1.5-4.5[19]
Electricity resource (cost)	Grid (71 USD/MWh)	Grid (71 USD/MWh)	Grid (71 USD/MWh)	Onsite gas turbine with carbon capture[20]	Grid (60 USD/MWh)
Thermal energy resource (cost)	Natural gas (5.69 USD/GJ)	Natural gas (5.69 USD/GJ)	Natural gas (5.69 USD/GJ)[21]	Natural gas (3.50 USD/GJ)	Natural gas (3.25 USD/GJ)

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[13] The gross cost of 376 USD/t_{CO2} corresponds to a novel Sulzer packing material created specifically for carbon capture (Mellapak-CC) optimized for the lowest gross cost of capture, whereas the high-end cost corresponds to the Mellapak-250Y packing optimized for the lowest net removed cost. Similarly, 518 USD/t_{CO2} value corresponds to Mellapak-CC optimized for the lowest net removed cost. The high-end cost (712 USD/t_{CO2}) corresponds to the Mellapak-250Y packing optimized for the lowest gross cost of capture.

[14] The cost range reported here is based on the natural gas scenario in the report with electricity sourced from the grid.

[15] This range corresponds to varying scenarios presented by Zeman. The low-end cost (309 USD/t_{CO2}) corresponds to a scenario with an onsite natural gas combined cycle facility with carbon capture and storage combined with heat integration and PVC-based packing. The high-end cost corresponds to a base case scenario consistent with that presented in APS report with a different energy load (calculations for energy load are shown in the paper)

[16] The costs reported here are consistent with scenarios A and B in the cited report at 7.5% and 12.5% annual capital recovery, respectively.

[17] For new technology such as DAC, a factor of 6 is used to account for uncertain scope and extra requirements of commercial-scale plants. An installed factor of 4.5 was used for the optimistic case, where an installed factor of 6 was used for the realistic case.

[18] Costs reported in Keith *et al* are based on engineering firm estimates using some results from pilot plant operation. The Lang factor presented here was back-calculated as the ratio of the total installed cost (M$1126.8) to the sum of the major equipment costs (M$347) (includes all equipment costs except other equipment and buildings)

[19] An installed factor of 1.5 was used for mature industrialized technologies (such as the slaker, causticizer, clarifier) and 4.5 for newer, less industrialized developments (such as the oxy-fired calciner).

[20] Alternative scenarios A and B use additional natural gas and an onsite turbine to produce electricity, however scenarios C and D, not included in this table, use grid electricity at 30 USD/MWh and USD/MWh.

[21] In the low natural gas cost case, Zeman uses a cost of 2.84 USD/GJ of natural gas. For all other cases, the table value is used.

	APS report [27]	Mazzotti et al. [67]	Zeman [68]	Keith et al. [8]	NASEM report [9]
Contactor configuration	Counter-flow	Counter-flow	Counter-flow	Cross-flow	Cross-flow
Packing materials	Mellapak-250Y	Mellapak-250Y Mellapak-500Y Mellapak-CC	Mellapak-250Y PVC-based	PVC-based	Stainless steel PVC-based[22]
Solvent solution	NaOH	NaOH	NaOH	KOH	KOH
Calciner technology	Oxy-fired	Oxy-fired	Oxy-fired	Oxy-fired	Oxy-fired
CO2 compression included?	Yes, 10 MPa	Yes, 10 MPa	Yes, 10 MPa	Yes, to 15 MPa	No

Review article by van der Spek et al. (2022)

Van der Spek et al. started from an observation on the DAC operative conditions [69][23]. They observed that the costs of a DAC plant depend on several factors including (1) the environmental conditions because temperature and humidity affects the capture rate and the units' efficiency, (2) the location of the facility since the electricity and heat sources prices depends on the geographical location, and (3) policies and future trends for the deployment of the DAC technologies. Indeed, this article takes into account the distinction between first-of-a-kind (FOAK) and nth-of-a-kind (NOAK), thus the learning curve, and their impact on the DAC plant TEA. FOAK denotes the first prototype plant built on industrial scale to prove the technology concept on large scale, to test stable operative conditions, demonstrate the technology, and have a first estimate of the economics. As more plants are built, the cost per unit of product will normally drop until the technology is mature, NOAK. In their work, Van der Spek et al. consider four technologies: KOH with Ca-looping (Carbon Engineering), KOH with bipolar membrane electrodialysis (BPMED), adsorption (Climeworks), and magnesium weathering[24].

Their analysis outlines results that are different from the claimed values by DAC companies. For instance, Climeworks is the only DAC company operating DAC facilities of some scale. They estimated from Orca plant that the DAC cost is ranging 500-600 USD/t_{CO2}, but the TEA models suggest for a FOAK solid-DAC that the costs are among 1250-3000 USD/t_{CO2}. They warn that these costs are perhaps not entirely comparable given the lack of information and details on the cost breakdown, and whether the Climeworks quote also includes compression, transport, and storage. Indeed, by neglecting the cost associated with CO_2 post-processing and assuming free waste heat source at the Orca plant, the quote drops to 570-900 USD/t_{CO2} which is close and consistent with Climeworks claiming. Similarly, Carbon Engineering early plant estimates

[22] This report presents a range for the cost associated with the capital equipment required for the process. Here, PVC-based packing was used for the low-end contactor cost and stainless steel for the high-end cost.

[23] The draft is still under the peer review process, and it is available in Chemrxiv (as an open-access article). However, due to the relevant content and solid results discussion, we are confident that the material should be included in the present report

[24] Magnesium weathering and high-temperature calcination is a proposed process (currently without a relevant industrial interest) which is very similar to the hot box of the Carbon Engineering process. For more details refer to McQueen, N., Kelemen, P., Dipple, G., Renforth, P., and Wilcox, J. (2020), *Ambient weathering of magnesium oxide for CO_2 removal from air*, Nat. Commun. 11, 3299

are around 190-260 USD/t_{CO2} for 100 000 t_{CO2}/y size liquid-DAC facility. The FOAK quote in the proposed study reveals that the cost should be higher 230-580 USD/t_{CO2}. In both cases, the authors considered to instal DAC plants in the United States paired with wind electricity. In their model, Van der Spek et al. do not consider the technology readiness level (TRL) which impacts on the economics[25].

Figure 10 shows the results of the TEA analysis. Regardless the technology, the economy of scale (i.e., the increment of the DAC size) helps to drop the cost for the capture CO_2. The giga-tons (1 000 000 000) scales will let the cost drop to 80-750 USD/t_{CO2}. The costs are 400-1600 USD/t_{CO2} when 100 000 t_{CO2}/y is considered, whilst the million-ton ranges 250-1200 USD/t_{CO2}. This suggests that the long-term policy goal in the United States (but also for all the DAC companies) of 100 USD/t_{CO2} may be challenging, yet not impossible, to surpass. The technology with the highest cost(at present) at any scale is the electrochemical dialysis (BPMED) due to the high electricity requirement (22 GJ/t_{CO2}). Figure 10 outlines the strong effect of the FOAK scale on the FOAK cost.

> *"The solid sorbent and KOH BPMED technologies with a smaller FOAK scale incur a higher FOAK cost as they cannot utilise economies of scale. However, these more modular technologies also exhibit higher learning rates as there are greater opportunities to improve and reduce costs when producing such modules through mass production. This leads to overlapping costs at similar scales across all four technologies. A reason behind the higher learning rate is their potential to gain learning from industries other than carbon removal, such as CO_2 supply to niche markets, i.e., via diversification. However, this does not apply solely to more modular technologies. For example, large-scale plants may be better suited to supply CO_2 to large-scale utilisation processes, such as a sustainable aviation fuel plant. Another important point is that the more modular technologies exhibit higher uncertainties in costs at scale. "*

[25] TRL impacts on the estimates of the costs for maintenance, material substitution, and any ancillary activity. Moreover, technology could benefit from the economy of scale which enables to progressively reduce as the technology catches on and starts to be deployed globally. Once the technology is well-established the supply chain helps to reduce the costs associated with items of costs previously listed (but not limited to only those).

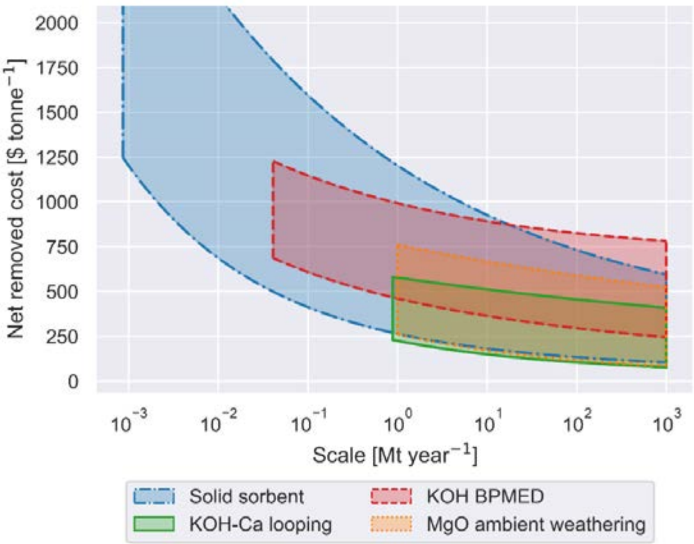


Figure 10 - Cost development trajectories of the four technologies from the kilo-ton to the gigaton CO_2 net removed per annum scale. Note the log scale on the x-axis. The cases studied are in the United States paired to wind electricity and using a heat pump for low-grade heat where applicable. The figure provides ranges instead of lines, highlighting a large amount of uncertainty and variability in the estimates (picture reproduced from Young et al., The cost of direct air capture and storage: the impact of technological learning, regional diversity, and policy, 2022, article under peer-review process and available in Chemrxiv https://chemrxiv.org/engage/chemrxiv/article-details/62c8275b252b2116a8df9365 under Creative Commons Attribution License CC BY)

The location of a plant has a key role in determining the cost estimates for DAC facilities (as shown in Figure 11 top chart and bottom one for FOAK and Gt_{CO2}/y scale plant, respectively capital expenses (CAPEX) are dominant for solid adsorbent technology, but they are a significant fraction also for liquid-DAC technology. The only exception is the BPMED technology. For this technology, the electricity, membrane maintenance/replacement (thus, variable OPEX) and possibly also membrane cost, drives the economics. However, as we move to a plant at the Gt_{CO2}/y scale, operating costs become more important for all technologies.

> *"To drive the cost down in the short term, we need to reduce the capital costs, which could come through process intensification or scaling-up and repetition. Whereas, to drive down the long-term costs in the future, we will need to focus on measures that can minimise the energy requirements for each process".*

Figure 11 (bottom) also shows that, as expected, the errors become a more significant proportion of the total cost at the giga-tons scale, mainly due to the uncertainty of projecting costs into the future via technological learning. Nevertheless, the intrinsic oscillations of the energy price (variable operating costs in Figure 11 legend) and of materials are factors to be accounted for. As a remark, (1) Figure 11-top (FOAK plant cost breakdown) shows that all the technologies are CAPEX-driven, while BPMED is the only one where electricity cost dominates the economics. (2) Thanks to the deployment of DAC facilities (from FOAK Figure 11-top to NOAK in gigatons scale deployment scenario Figure 11-bottom) costs are expected to drop from 400 – 2500 USD/t_{CO2} for FOAK to 150 – 800 USD/t_{CO2} for NOAK gigatons capacity (neglecting the uncertainty bars for both scenarios). (3) The capital investments (CAPEX) will reduce substantially thanks to the technology scale-up and deployment, and industrialization of the module/special materials/units' production. This will lead to a cost breakdown where the operational costs (labour, operational and maintenance) will make up the most significant item of cost for DAC technologies. This aspect has been already discussed in section Review of the TEA from recent works on DAC. (4) These considerations are location independent since based on economy of scale basic principles.

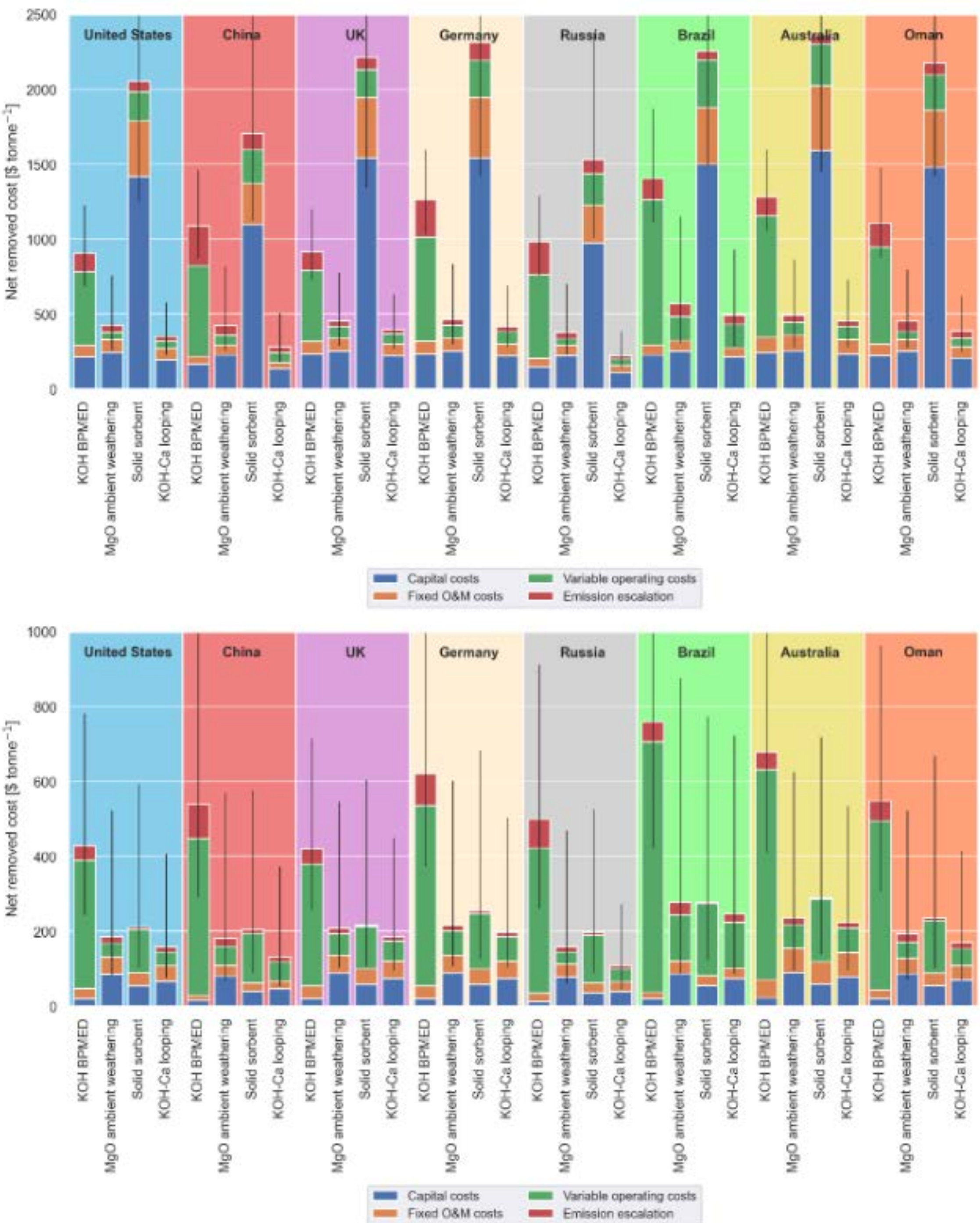


Figure 11 - Top: Breakdowns of the FOAK net removed costs for every technology in each country paired with wind electricity and a heat pump for low-grade heat where applicable. Bottom: Breakdowns of the Gt_{CO2}/y scale net removed costs for every technology in each country paired with wind electricity and a heat pump for low-grade heat where applicable. The black lines are the error bars on both graphs, and the emission escalation represents the cost escalation from gross capture cost to net removed cost due to GHG emissions from energy usage. Note the difference in y-axis ranges in both figures (picture reproduced from Young et al., The cost of direct air capture and storage: the impact of technological learning, regional diversity, and policy, 2022, article under peer-review process and available in Chemrxiv https://chemrxiv.org/engage/chemrxiv/article-details/62c8275b252b2116a8df9365 under Creative Commons Attribution License CC BY)

Expert elicitation survey

Tavoni et al. published the results from a elicitation survey proposed to 18 experts in DAC technologies [70]. The survey pool included academics, experts in business development for novel technologies, key figures involved in energy economics and policy, and experts in DAC development.

> *"The survey was structured in three sections: (1) assessing the cost and capacity of DAC technologies under two different scenarios and climate policies, (2) identifying the current and future technical requirements for DAC deployment in terms of energy, temperature, land allocation and other relevant features, and (3) evaluating critical non-technical factors including growth barriers and supporting policies that will influence the future deployment of DAC facilities. The two scenarios proposed at the point (1) are the policy as usual (PAU) meaning that international agencies and governments will take no additional specific actions to contrast the climate change and a stringent climate policy consistent with the 2°C target (2DC). Under each scenario, experts were first asked to choose a technology that they thought will be the dominant DAC technology in 2050. Then they provided the 10th, 50th, and 90th percentiles of the cost and annual installed capacity of the chosen DAC technology in the present (year 2020) and in the future (year 2050). The current cost estimates of DAC technologies vary based on the material used in the capturing process and other assumptions about the capturing and regeneration units' design"*.

For all additional questions, experts were asked to provide further information referring only to the PAU scenario and DAC technology choice under this scenario. It is noteworthy that the survey is anonymous, and it is not possible to know the identity who made the corresponding estimate. The results and comments are directly taken from Shayegh, Bosetti, and Tavoni, (2021), *Future Prospects of Direct Air Capture Technologies: Insights from an Expert Elicitation Survey*, Front. Clim. 3:630893 [70]. These results and the statistics are interesting and relevant, even though some replies to the survey (done in 2018-2019) refer to 2020. It is possible to compare the experts' predictions with the status of DAC and realise how their forecasts were close or far to the current deployment and estimates.

The authors compared the estimates from the experts survey with respect to

> *"the lower-bound and upper-bound of the NASEM net removal cost estimates for liquid solvent DAC: 156 USD/t_{CO2} for a system with high-efficient solar energy and 506 USD/t_{CO2} for a low-efficient system with wind energy, respectively (grey shaded area in Figure 12). The analysis shows that out of five experts who chose the liquid solvent DAC system in the PAU scenario, two reported median net removal cost estimates larger than the NAS upper-bound. They also reported a much smaller reduction in the future cost estimates compared to the other experts. The three other experts, however, not only reported a sharp decline in the median net removal cost in 2050 compared to 2020, but also expressed a considerably smaller uncertainty over the future cost values. The reduction in the median net removal cost is more evident when comparing the aggregate cost estimates in 2020 and 2050 in where the aggregate median net removal cost goes down from 453 [251, 1150] USD/t_{CO2} in 2020 to 275 [135, 1150] USD/t_{CO2} in 2050 under PAU scenario. The cost reductions from 2020 to 2050 are even more profound in the 2DC scenario. In this case, all four experts who chose the liquid solvent DAC system indicated a reduction in the median cost and the uncertainty over it in 2050 compared to 2020. Further insights in the statistical analysis show that net removal cost goes down from 453 [222, 837] USD/t_{CO2} in 2020 to 214 [124, 445] USD/t_{CO2} in 2050 under 2DC scenario"*.

The NASEM range for the solid sorbent DAC is reported as orange shaded area in Figure 12. The lower-bound and upper-bounds are 89 USD/t_{CO2} (system with high-efficient solar energy) and 877 USD/t_{CO2} (low-efficient system with coal energy), respectively. A most recent study has put the capture cost of solid sorbent DAC in the range of 120–155 USD/t_{CO2} [71].

In the study, most of the 2020 net removal cost median estimates are consistent with the NASEM report range as shown in Figure 12. Only one expert (expert 8) reported the median net removal cost larger than the NASEM upper-bound. However, the 2020 net removal cost uncertainty ranges vary greatly among the experts while the uncertainty ranges are smaller for the 2050 net removal cost estimates. This is not surprising since the confidence with DAC technologies is expected to grow progressively. As for the liquid solvent DAC, both the median estimates and uncertainty ranges reduce under 2DC scenario thanks to a stronger deployment. The statistics on the survey replies shows net removal cost with solid sorbent technology going down from 624 [336, 1035] USD/t_{CO2} in 2020 to 336 [158, 631] USD/t_{CO2} in 2050 under PAU scenario. On the other hand, under 2DC scenario average median of the net removal cost with solid sorbent technology drops from 591 [314, 1143] USD/t_{CO2} in 2020 to 207 [77, 691] USD/t_{CO2} in 2050 under 2DC scenario. The cost reduces more than half and experts probably rely on more incentives due to “contingencies” to match more pressing environmental targets.

In summary, these graphs can be used to compare the results in terms of average net removal cost estimate and the uncertainty range around it across time. Further, median cost estimates for both technologies are expected to drop regardless of the scenarios, but the costs drop is more evident under 2DC scenario since more drastic countermeasures should be deployed. The uncertainty over net removal cost is generally smaller in 2050 compared to 2020 for each expert and the aggregated results and this is normal considering the expected increasing confidence in the technology though learning-by-doing. More experts favoured solid sorbent technology and the individual uncertainty ranges are generally larger for this type of DAC technology not surprisingly due to the novelty and lower level of confidence with the adsorption processes. It is interesting to note that almost 30% (5 experts) of the interviewed experts changed the technology which could help to fit environmental target fixed in the two scenarios. Three experts (14, 15, and 17)) changed the choice of the liquid-DAC for PAU scenario to solid-DAC in 2DC one, and two experts (4 and 7) made the opposite. Four experts (25% of the pool) have not selected any “winning” technology and they only preferred to suggest the global capacity (Figure 13).

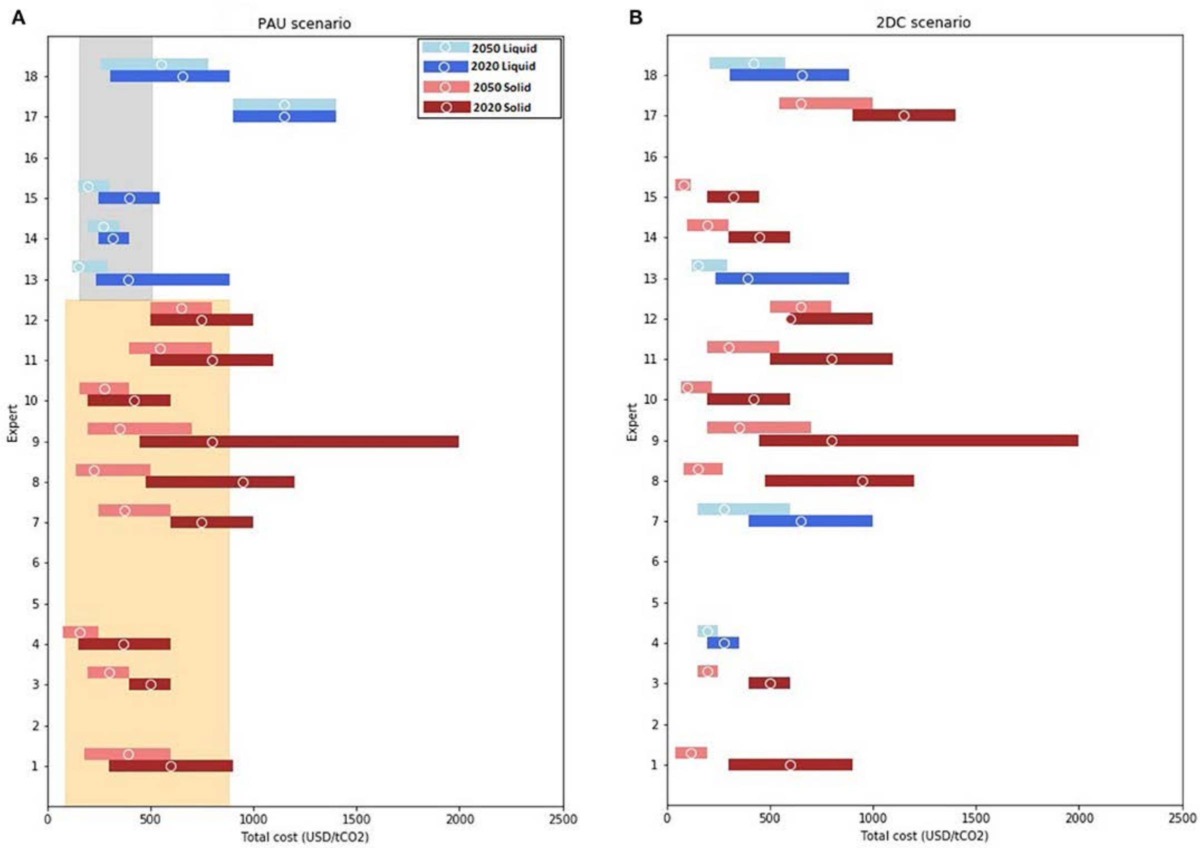


Figure 12 - Total net removal cost estimates (50th, 90th, and 10th percentiles) for solid sorbent (red bars) and liquid solvent (blue bars) technologies under (A) PAU scenario and (B) 2DC scenario. The results are reported for 2020 (dark colors) and 2050 (light colors) for each expert. The orange and gray boxes indicate the range of values reported in the National Academy of Sciences reports for solid sorbent and liquid solvent technologies respectively. Experts 2, 5, 6, and 16 did not provide answers to the cost estimate questions (picture reproduced from Shayegh et al., Future Prospects of Direct Air Capture Technologies: Insights from an Expert Elicitation Survey, 2021, Front. Clim. 3:630893. doi: 10.3389/fclim.2021.630893 under Creative Commons Attribution License CC BY)

In addition to costs, experts provided information about expectations on the future deployment of DAC technologies. In Figure 13, probabilities concerning annual installed capacity (AIC) are reported for both technologies under the proposed two scenarios. First, there are very few installed DAC facilities, and therefore, the experts provided near-zero estimates for 2020 values. Second, only five experts estimated that the median AIC of solid sorbent systems will be above 100 mill. t_{CO2} in 2050 but none of them provided an AIC estimate above 1 Gt_{CO2}. On the other hand, two respondents estimated that AIC of liquid solvent system will go beyond 1 Gt_{CO2} in 2050. This highlights the potential of a liquid solvent system in delivering high-capacity removal in large scales. Under 2DC scenario, however, the median AIC estimates increase significantly for both technologies in 2050. However, the uncertainty ranges are wider in both groups for individual experts and aggregated estimates. The experts think about the role of DAC in shaping the mitigation portfolio under each scenario regardless of the type of technology being used. Regardless of large uncertainties over the AIC estimates, it is common opinion among the experts that DAC could contribute to reaching the 2°C climate target by removing up to tens of Gt_{CO2} by mid-century under 2DC scenario. Noteworthy, experts 5 and 16 provided forecasts for DAC global capacity only for scenario 2DC. Probably, they considered that DAC deployment will be favoured only under more pressing scenario and more ambitious environmental targets.

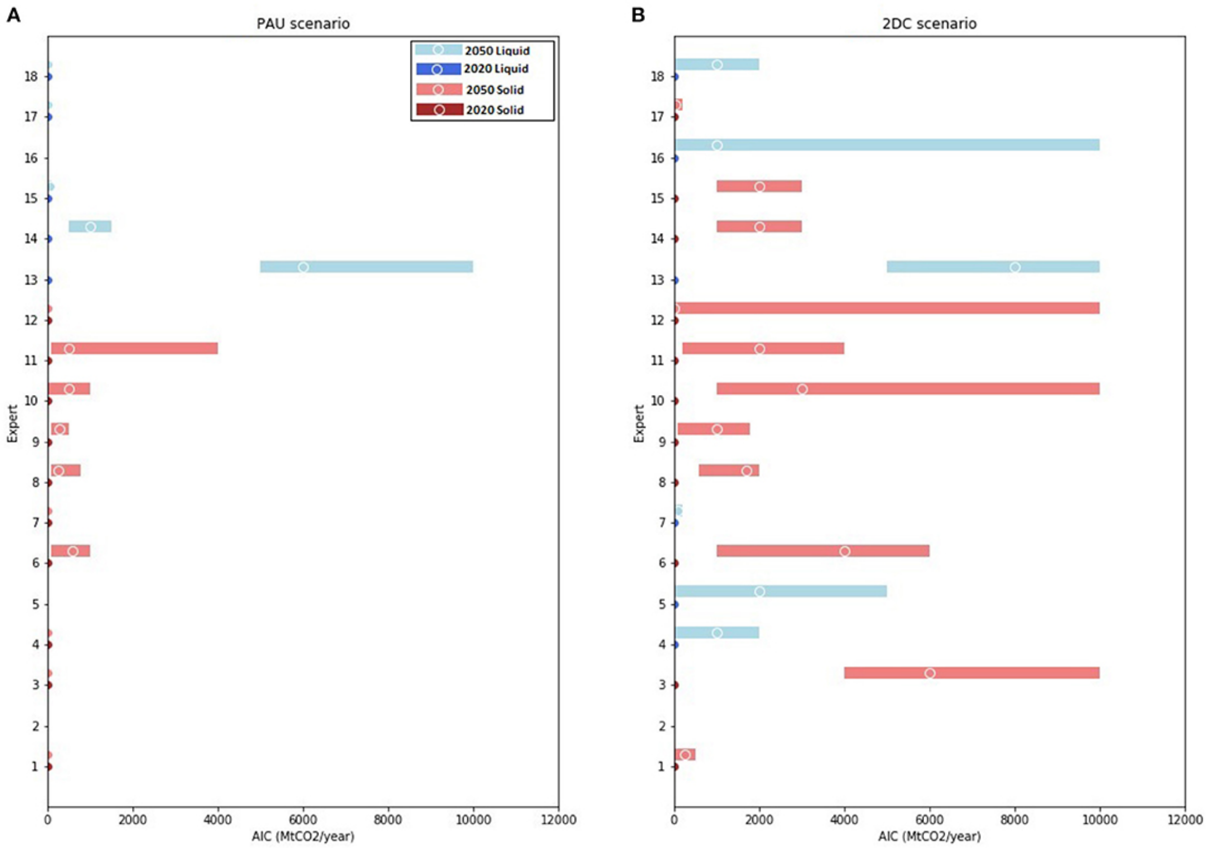


Figure 13 – Annual installed capacity (AIC) of DAC (50th, 90th, and 10th percentiles) for solid sorbent (red bars) and liquid solvent (blue bars) technologies under (A) PAU scenario and (B) 2DC scenario. The results are reported for 2020 (dark colors) and 2050 (light colors) for each expert. The 2020 values are near zero and negligible. The red bars show the solid sorbent technology and the blue bars represent the liquid solvent technology. Experts 2 did not provide answers for the AIC estimate questions. Experts 5 and 16 provided estimates only for 2DC scenario (picture reproduced from Shayegh et al., Future Prospects of Direct Air Capture Technologies: Insights from an Expert Elicitation Survey, 2021, Front. Clim. 3:630893. Doi: 10.3389/fclim.2021.630893 under Creative Commons Attribution License CC BY)

> *"The experts provided estimates for each technology's evolution in required energy, temperature, and land in addition to the cost and capacity estimates. The detailed results for these parameters are provided in Figure 14. Liquid solvent DAC technologies, in general, require more heat during the regeneration process. Processing solid sorbent DAC technologies, on the other hand, is less energy-intensive and it requires a lower temperature. Energy requirements estimates in this survey are generally higher than those reported by the NASEM report. The median estimate for solid sorbent technologies is around 8 GJ/t_{CO2} in 2020 while the NASEM estimates range from 4 to 6 GJ/t_{CO2}. However, the experts estimated that the median energy requirements for solid sorbent systems will drop to about 6 GJ/t_{CO2} by 2050 which falls at the upper-bound of the NAS estimate range. On the other hand, the median estimate for liquid solvent technologies is around 10 GJ/t_{CO2} in 2020, within the range of NASEM estimates (8–12 GJ/t_{CO2}). The experts estimated that liquid solvent systems median energy requirements will drop to about 8 GJ/t_{CO2} by 2050".*

The land allocation (Figure 14c) shows that there is a wide a range for the solid-DAC facilities. It is not clear if the experts considered only the DAC plant, or they included also the energy "farm". What it is clear is the uncertainty associated with solid-DAC. Once again, this demonstrates that the lower confidence of the experts with solid-DAC.

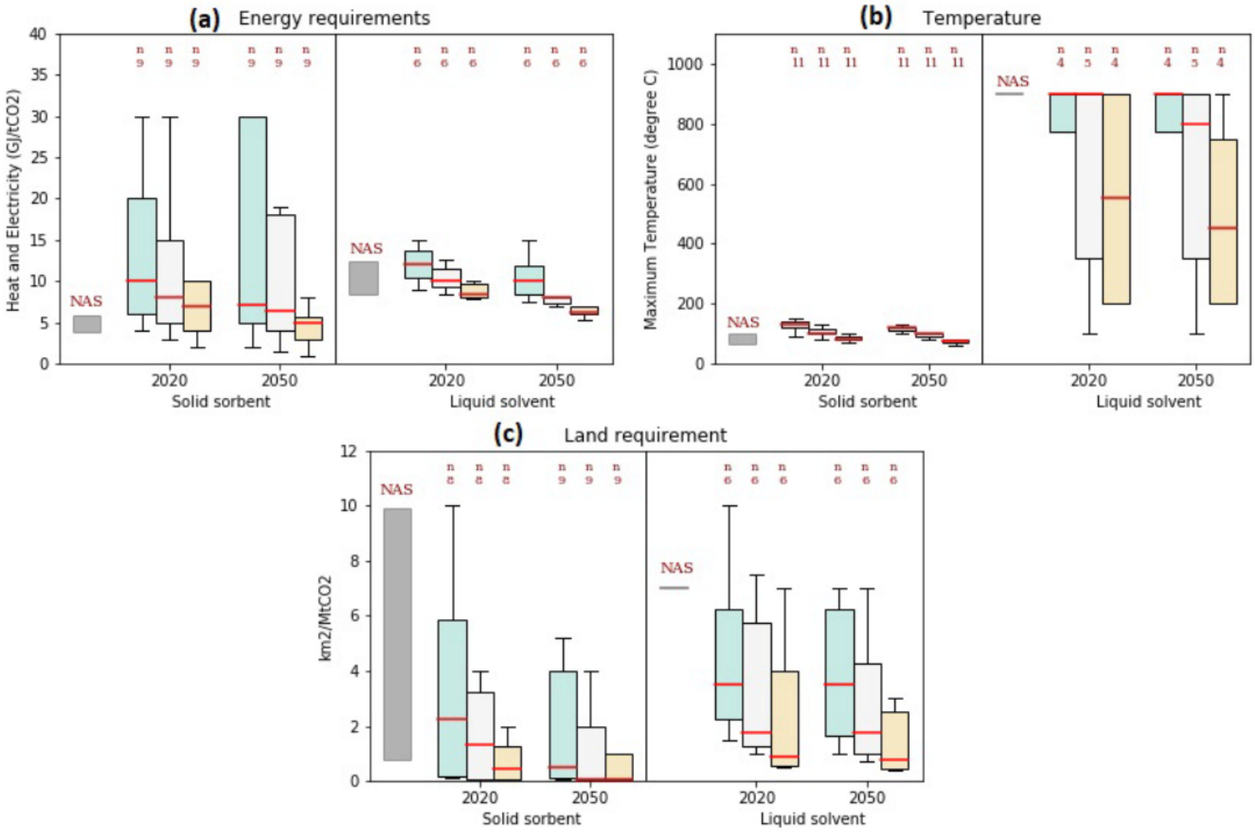


Figure 14 - Energy, temperature, and land requirements as the combination of heat and electricity for solid sorbent and liquid solvent technologies under PAU scenario. The results are reported for two years (2020 and 2050). The green, white, and range boxes show the high, median, and low estimates respectively. The box plots show first, second (median), and third quartiles of the distribution. The whiskers indicate the maximum and minimum values. The gray box indicates the range of values reported in the reports by the National Academy of Sciences, Engineering, and Medicine (NASEM, here reported as NAS). The numbers at the top indicate the number of recorded responses in each category (picture reproduced from Shayegh et al., Future Prospects of Direct Air Capture Technologies: Insights from an Expert Elicitation Survey, 2021, Front. Clim. 3:630893. doi:10.3389/fclim.2021.630893 under Creative Commons Attribution License CC BY)

IEAGHG report (2021) and IEA report (2022)

FOAK and NOAK distinction

The IEAGHG and IEA reports [6,7] provide some a more detailed insight on the DAC costs drop. These reports insist on the distinction between first-of-a-kind (FOAK) and nth-of-a-kind (NOAK) and their impact on the DAC plant TEA[26]. The drop of the costs is driven by several factors (Figure 15). Research and development (R&D), learning-by-doing (LBD), the economy of scale contributes to this effect. According to the main technology providers, capture costs are expected to decrease substantially in the next five to ten years, underpinned by a major increase in DAC deployment worldwide, from the thousand-tons scale to the million-tons scale. The anticipated fall in cost from the first large prototype (FOAK) to the NOAK plant has been attributed to specific components as well as improved constructability and well-established supply chains.

[26] FOAK denotes the first prototype plant built on industrial scale to proof the technology concept on large scale to demonstrate the feasibility and have a first estimate of the technology economics. When a technology catches on and other plants are built, the costs estimates drop referred to NOAK since other plants beyond the first one is going to be operated.

"For liquid-DAC the expected cost reduction from FOAK to NOAK is 27%, of which 42% comes from a single key equipment: the air contactor. While this unit is based on commercial cooling-tower technology, its expected cost reduction comes from several modifications to the standard commercial design, including packing geometry (allowing for cross flow exchange between solvent and air) and depth (reducing pressure drop and increasing packing wetting and therefore performance). For solid-DAC, technology providers are expecting a threefold to six-fold cost reduction in the short to medium term [72]. *Performance improvement is expected to come mainly from innovative solvents able to reduce DAC-specific energy consumption ("learning by researching") and from technology spillovers from other sectors and applications".*

Further cost reduction can be driven by deployment (and the associated "learning") and economies of scale:

- **Learning by researching (R&D)**: much DAC research focuses on reducing the energy consumption needed to separate CO_2 at low concentrations from atmospheric air. Compared to established technologies such as solid-DAC (S-DAC for simplicity) and liquid-DAC (L-DAC), emerging separation technologies (for instance, electro-swing adsorption and bipolar membrane electrodialysis) could require less energy per ton of CO_2 (more optimistic projections estimate up to 90% energy savings). This huge potential comes from innovative approaches to regenerating the solvent at low to medium temperatures, or by different CO_2 separation techniques (e.g. membrane-based separation).
- **Learning-by-doing**: *"technology deployment drives costs down as experience in designing, producing, commissioning and operating DAC plants accumulates along a learning curve. Within the energy system, learning rates (quantifying the steepness of the learning curve: the higher the learning rate, the steeper the learning curve, the faster the cost decrease) have ranged between 10-15% on average* [73]*, with exceptionally rapid drops for specific, very successful technologies such as solar PV (around 20%). For DAC technologies, L-DAC has been compared in the literature to more traditional amine-based, point-capture technologies (which are currently already commercial) and are therefore expected to have a 10% learning rate, while S-DAC is expected to have higher learning rate (around 15%) due to its modular nature* [71]*."*
- **Economies of scale**: *"these represent cost advantages related to either mass production of a certain piece of equipment or the production of the same equipment at a larger scale compared to its initial design. Mass production allows for shared infrastructure and facilities and relies on an optimised supply chain. Economies of scale benefit small, modular units that can be mass produced (such as S-DAC modules), and large equipment (such as those required for L-DAC) whose cost becomes cheaper per unit of output than the same equipment on a smaller scale. Modular systems undergoing mass production, such as household appliances, have historically seen a steep decrease in price. As an example, the price of air-conditioning units decreased by 21% between the early 1990s and early 2010s* [74]*, while their energy efficiency performance increased. They have multiple similarities with solid-DAC due to the presence of a rotating element (i.e., a fan), cooling and drying loops, and closed and open circuits. For large-scale units, the "rule of 6/10" gives satisfactory results (i.e., within a 20% margin of error). It estimates a cost reduction proportional to six tenths of the ratio between the size of a large-scale unit and a small-scale unit. For L-DAC, this would mean a cost reduction of more than 50% per ton of* CO_2 *captured when scaling up from for example 1 Mt of capture capacity to 5 Mt".*

Nevertheless, it is worth highlighting that the cost drop influences exclusively the investment costs (CAPEX) since the operational costs (OPEX) depends on energy, utilities, and labour market fluctuations. For this reason, CAPEX should be decrease at minimum to reduce the investments to build the plant (materials, infrastructures, and ancillary units), while OPEX should be optimized to reduce the impact of the external factors such the electricity costs, utilities consumptions (cooling water, waste heat, and so forth), and more in general energy costs. The final target is minimizing the exposition of the technology to external events and making stable and affordable the technology operation and deployment.

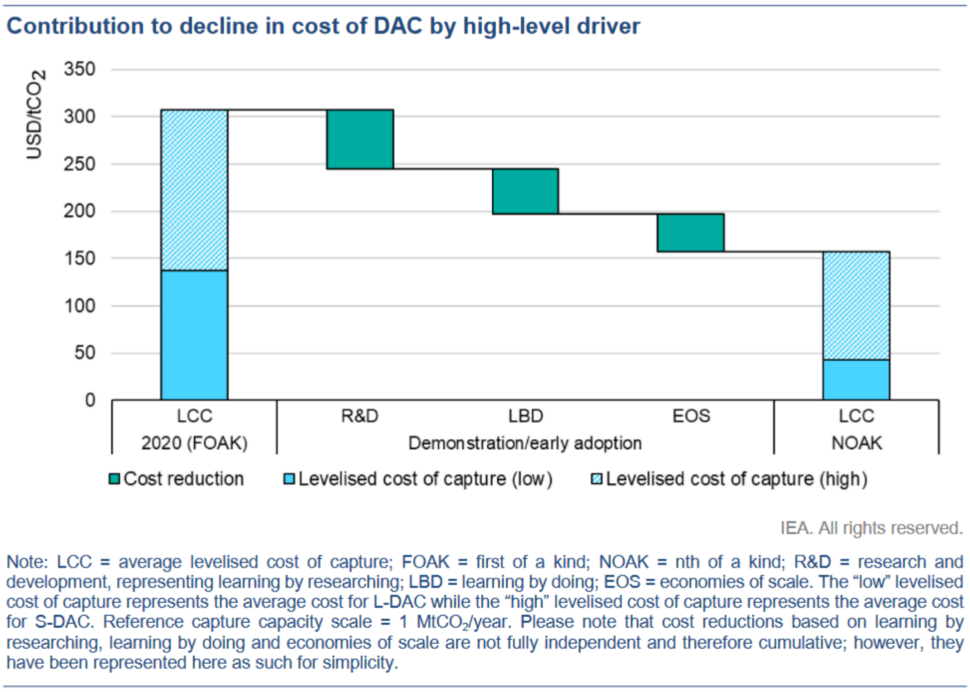
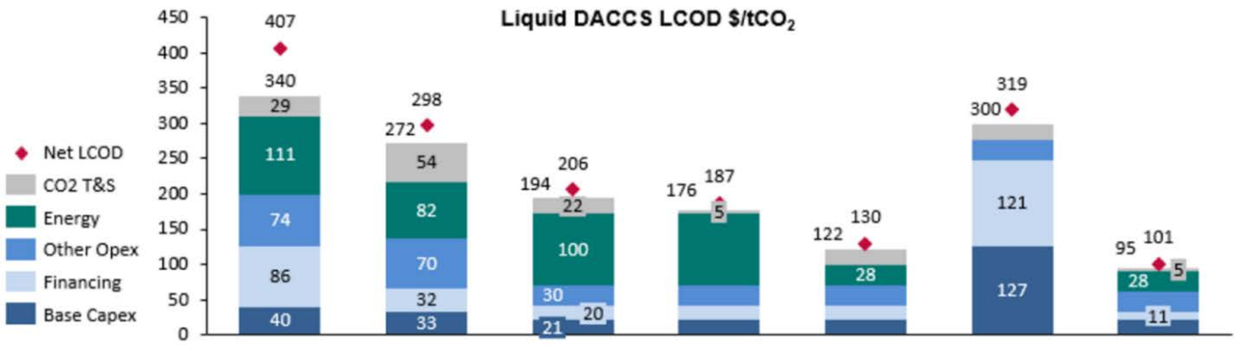


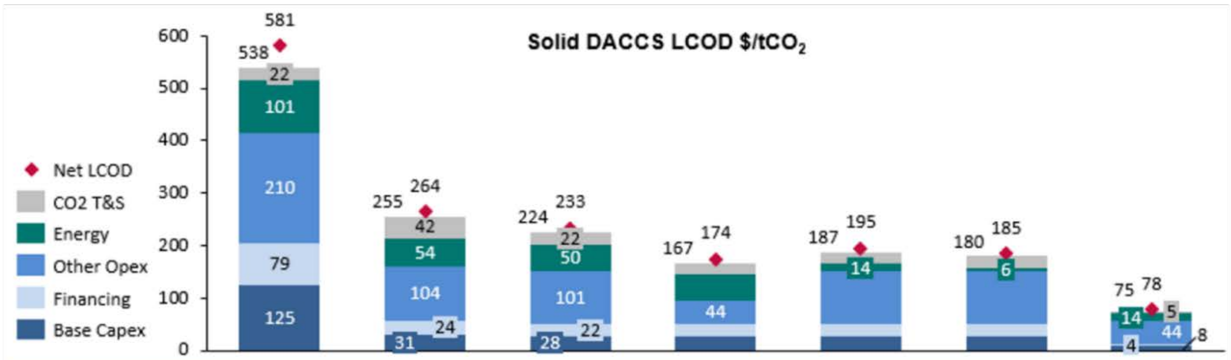
Figure 15 – Factors affecting the costs drop of a novel technology from the FOAK to the NOAK (picture reproduced with permission from the International Energy Agency, Direct Air Capture – A key technology for net zero, IEA report, 2022, all rights reserved)

Regardless of the technology, the costs reduction trend for DAC technologies is straightforward as also reported in IEA guidelines. There are two interesting observations. First, the drop is sensitive to the deployment and the global capture rate. The larger are the deployment and global volume of CO_2 captured through the DAC, the more DAC cost benefits in terms of CAPEX reduction. The CAPEX cut is more evident at the beginning when the technology enters the market (for industrial validation) and starts attracting attentions and investments, and at the conclusion of the industrialization steps when it is fully developed, and the global deployment Further boosts the costs. In the middle (i.e., during the development and testing) the costs drop is less effective due to progressively improvements and slow scale up step-by-step process. For instance, this is what we are facing with Climeworks technology. Refer to Review article by McQueen et al. (2021) paragraph for additional details.

Figure 16 summarises the potential of the different DAC technologies over several scenarios including (1) plant size, (2) energy inputs, thus, fully electric-driven DAC and system where both heat and electricity are supplied (hybrid), (3) different scenarios for the energy costs. Finally, the last column (denoted as 'very ambitious') refers to cases where the costs for the electricity and storage are assumed to Further drop with respect to the base case. The FOAK cost ranges in 400-600 USD/t_{CO2} (including the LCA, red dots in Figure 16). The results of the TEAs show that liquid-DAC is the best solution for the FOAK and the gap between the two technology depends on the adsorbent material, which is expensive, but the economy of scale should help to reduce the impact of this element over the DAC economics. Conversely, the solid-DAC is a relatively novel technology if compared to the liquid-DAC. Indeed, the liquid-DAC relies on conventional equipment such as pellet reactor, slaker, and calciner. These units are well established in the process engineering practice. Thus, the cost for the FOAK is lower since their design is relatively known. The air contactors are the only innovation in liquid-DAC since they are tailored to minimise the gas pressure drop while preserving a high contact surface area for CO_2 capture. The solid-DAC include a series of novel elements such as the module and the adsorbent formulation. The higher number of novel elements implies more room for R&D and improvements. Hence, the cost for solid-DAC could decrease more effectively. The LCOD ranges 175-320 USD/t_{CO2}, but in more optimistic scenario it could drop below 100 USD/t_{CO2}.



Case	1- Early Hybrid	2- Small Plant	3- Base Electric	4- Low T&S Cost	5- Low-Cost Solar	6- Flexible Operation	7- Very Ambitious
Maturity	FOAK	NOAK	NOAK	NOAK	NOAK	NOAK	NOAK
Technology	Hybrid	Hybrid	Electric	Electric	Electric	Electric	Electric
Capex, Fixed Opex, Consumables	Base Case- Early Plant	Base Case- 100kt/yr Plant	Base Case	Base Case	Base Case	15% Plant Utilisation	Base Case
Electricity Source	Solar PV – Base Case ($68/MWh)	Solar PV – Base Case ($50/MWh)	Solar PV – Base Case ($50/MWh)	Solar PV – Base Case ($50/MWh)	Solar PV – Low ($14/MWh)	Free Solar PV	Solar PV – Low ($14/MWh)
CO_2 T&S	Base Case ($22/tCO$_2$)	Base Case ($22/tCO$_2$)	Base Case ($22/tCO$_2$)	In Cluster ($5/tCO$_2$)	Base Case ($22/tCO$_2$)	Base Case ($22/tCO$_2$)	In Cluster ($5/tCO$_2$)
Cost of Capital	10%	5%	5%	5%	5%	5%	3%



Case	1- Early Hybrid	2- Small Plant	3- Base Electric	4- Low-Cost Adsorbent	5- Low-Cost Electricity	6- Low-Cost Energy Hybrid	7- Very Ambitious
Timeline	FOAK 2020s	NOAK 2050s	NOAK 2050s	NOAK 2050s	NOAK 2050s	NOAK 2050s	NOAK 2050s
Technology	Hybrid	Hybrid	Electric	Electric	Electric	Hybrid	Electric
Capex, Fixed Opex, Consumables	Base Case- Early Plant	Base Case- 100kt/yr Plant	Base Case	Low Sorbent Cost	Base Case	Base Case	Low Sorbent Cost & High Learning Rate
Electricity Source	Solar PV – Base Case ($68/MWh)	Solar PV – Base Case ($50/MWh)	Solar PV – Base Case ($50/MWh)	Solar PV – Low ($50/MWh)	Solar PV – Low ($14/MWh)	Solar PV – Low ($14/MWh)	Solar PV – Low ($14/MWh)
Heat Source	Nuclear ($19/MWh)	Nuclear ($19/MWh)	-	-	-	Free Waste Heat	-
CO_2 T&S	Base Case ($22/tCO$_2$)	Base Case ($22/tCO$_2$)	Base Case ($22/tCO$_2$)	Base Case ($22/tCO$_2$)	Base Case ($22/tCO$_2$)	Base Case ($22/tCO$_2$)	In Cluster ($5/tCO$_2$)
Cost of Capital	10%	5%	5%	5%	5%	5%	3%

Figure 16 – Charts and tables showing technical parameters describing key liquid and solid DAC cases and breakdown of associated gross and net costs. Base cases showing long-term electric plant parameters are highlighted. Parameters which are same as the base case are faded (picture reproduced with the permission from Element Energy's and IEAGHG report, Global Assessment of Direct Air Capture Costs, 2021)

Transport and storage

Figure 16 gives transportation and storage costs for several cases. The IEAGHG report gives not enough details to be able to use this for estimating transport and storage costs for a Norwegian case. The CO2LOS project supported by the CLIMIT programme is developing a flexible model for calculating cost of intermediate storage and transport.

Sensitivity analysis on the estimates for large-scale NOAK

IEA reports also the sensitivity analysis of a large-scale DAC costs based on the current projections on the technology. The analysis is useful to understand the importance and impact of key parameters on overall DAC costs, a sensitivity study is performed by varying the values of selected parameters by certain amounts and calculating resulting LCODs (Levelized Cost of DAC). As in case of novel technology or at early-stage development, the sensitivity analysis is necessary since the DAC facilities deployment is still limited, thus, the LCOD projection is full of uncertainties and lacks "industrial data" to corroborate these results could lead to large underestimate of the real costs associated with this kind of technology. Thus, the sensitivity analysis helps to detect the main parameters which could cause large oscillations in the LCOD.

Figure 17 and Figure 18 summarise the outputs of the sensitivity analysis performed on NOAK 1 mill. t_{CO2}/year capacity liquid and solid hybrid plants, respectively. The columns on the right indicate how much the parameters were changed, and the bars show the percentage shift on total net LCOD. Hybrid plants were used as opposed to electric-only configurations to be able to assess impact of heating costs. CAPEX and electricity prices (variable OPEX) were the most influential parameters on overall liquid DAC costs, demonstrating the importance of access to cheap electrical energy once again.

Cost of capital was found to have moderate impact, therefore securing affordable finance can be a useful enabler for future DAC deployment. CO_2 transport and storage (T&S) costs were another moderately influential component, especially because liquid systems transport and store more CO_2 than originally captured from air. As discussed in more detail in the next section, locating a DAC plant in a CCS cluster can significantly reduce T&S costs if infrastructure is shared.

Natural gas prices have the potential to impact costs, but variation of this parameters is supposed to be limited. Lastly, liquids LCODs are not sensitive to solvent and other consumable prices since these are common chemicals with already relatively low costs and large volume production. Compared to liquids, the most significant difference of solid DAC sensitivity is the very high impact of adsorbent prices. Adsorbent cost is a product of adsorbent performance and unit costs. There is usually a trade-off between better performing/longer lasting adsorbents and unit adsorbent costs. Still, further R&D and economies of scale can improve adsorbent economics, which can increase cost-effectiveness of solid DAC. As pointed out in Young et al. [75], at the current state the largest uncertainties in the design of adsorbent are associated with the CO_2 mass transfer/adsorption kinetics, heat of adsorption, solid heat capacity and thermal conductivity, and thermal stability. On average, these parameters heavily affect the energy requirement for the solid-DAC. For instance, the kinetic influences the amount of material required for the DAC air contactor, the heat of adsorption and solid material physical properties the heat required for the regeneration, and finally, the thermal stability is directly connected to the maintenance and replacement rate of the adsorbent material.

> *"Solid DAC costs display less sensitivity to electricity and CO_2 T&S prices compared to liquids due to lower power demands and volumes of CO_2 processed. Heat prices are found to have moderate impact on solid DAC costs. Some studies in the literature assume waste heat to be free of charge, but our analysis shows that heat can be a considerable cost component if it is not free. Lastly, sensitivity of costs to plant lifetimes is noteworthy for both solid and liquid plants. Higher lifetimes do not reduce costs significantly due to discounting of future expenditure. However, halving of NOAK plant lifetimes is found*

to increase LCODs significantly, especially for solid DAC plants, which have lower overall lifetimes than liquids. Thus, in long-term projections, the solid-DAC seems to be the more economically appealing and affordable technology to be operated both on small- and large-scale for the deployment of negative emissions technology (NET)".

The above discussion is provided for hybrid NOAK plants, however, sensitivities for other configurations are expected to differ slightly.

"For example, electricity-only plants would have no sensitivity to heating costs or methane leakage, whereas electricity prices would be much more influential. This implies that full electric plants would be well-suited regions with the cheapest low-cost power, whereas hybrid plants would be better suited regions with natural gas abundance and limited renewable access. Since upfront capital investment and financing costs are higher for FOAK plants, early stage DAC costs will show much higher sensitivity to CAPEX and cost of capital. Methane leakage and adsorbent prices are also expected to be more influential for FOAK plants because the proposed model in IEAGHG report assumes significant reduction in both parameters in the future. On the other hand, heating and CO_2 transport and storage (T&S) prices are expected to have much less impact on FOAK costs because they are external to capture plants and are not assumed to improve substantially over the next 30 years".

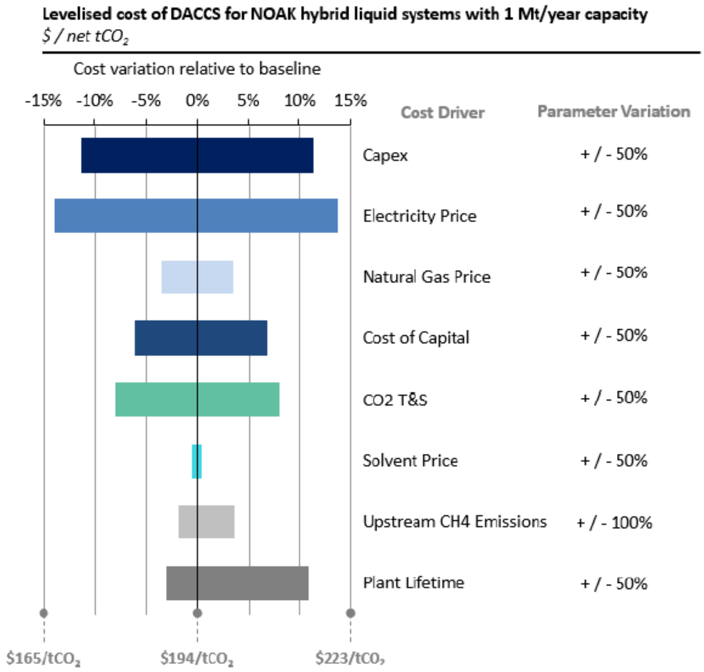


Figure 17 – Sensitivity of 1 mill. t_{CO2}/year capacity NOAK hybrid[27] liquid DAC costs in USD/t_{CO2} net (picture reproduced with the permission from Element Energy's and IEAGHG report, Global Assessment of Direct Air Capture Costs, 2021)

[27] Hybrid denotes plants using both heat and electricity, the alternative is a fully electricity-driven DAC (for both liquid- and solid-DAC. According to the experts, this option will be available later than 2030.

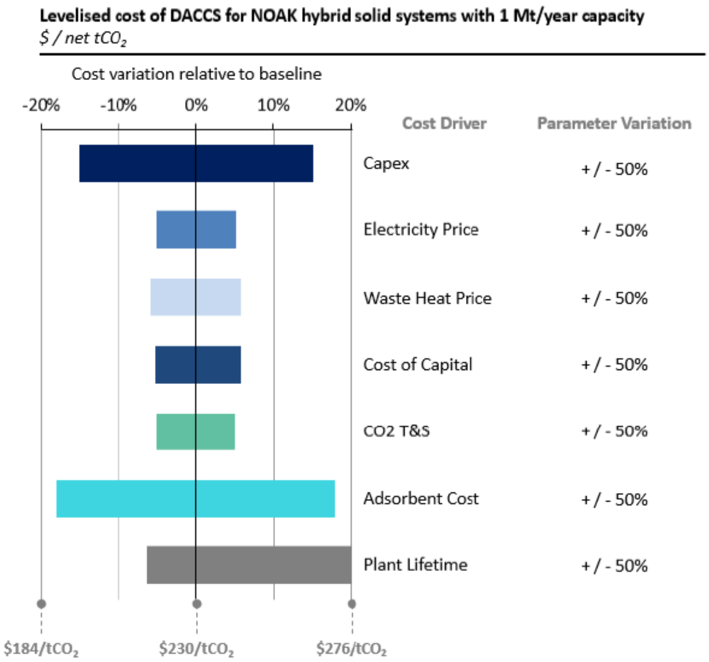


Figure 18 – Sensitivity of 1 mill. t_{CO2}/year capacity NOAK hybrid solid DAC costs in USD/t_{CO2} net (picture reproduced with the permission from Element Energy's and IEAGHG report, Global Assessment of Direct Air Capture Costs, 2021)

Conclusions and resume on the independent estimates

As pointed out in all the reports and published works, both liquid and solid DAC present advantages and disadvantages (Table 3). Despite most of the experts being not fully aligned on the DAC technologies, economics and estimates, potentials, deployment, and locations (as reported in section Expert elicitation survey), they are confident that there is the possibility for improvements both for the adsorbent and the liquid absorbent . A comparison is very complex since all the technologies do not share the same technology readiness level (TRL).

Further, Figure 19 depicts the key findings from the TEA assessments. Some of the points will be further discussed in the next paragraphs. Below is an overview and discussion around the sources of data used to model liquid and solid DAC technologies and inherent uncertainties related to these technologies.

Liquid DAC data uncertainties:

- Carbon Engineering's 1 mill. t_{CO2}/year hybrid DAC plant CAPEX estimate is based on a FEL-2 (front end loading) level of analysis where all major equipment costs are based on technically and commercially evaluated budgetary quotes from multiple vendors at the plant scale. This level of estimate is more detailed than most other kinds of costs estimate in the DAC literature. Still, a large-scale plant is not built to date, so there are inherent uncertainties in all costs compared to more established technologies (for instance post-combustion capture).
- Using the current information, it is not possible to reproduce the simulation proposed in Keith et al.; hence, we use reported results without having access to experimental data and implemented flowsheets. These missing details on the energy and material balances should be accounted as additional uncertainty for the liquid-based technology.
- The IEA report scales the CAPEX from a known scale (namely, 1 mill. t_{CO2}/y) to estimate the CAPEX for a different scale. This approach leads a lower level of accuracy. Costs for electric plants,

especially the next generation electric plant, and the cost reduction of NOAK plants are also estimates with much higher uncertainties.

Solid DAC data uncertainties:

- Publicly available cost data on solid DAC technologies are typically based on pure academic work and carry higher inherent uncertainties compared to liquids. As pointed out in Young et al. [75], at the current state the largest uncertainties in the design of adsorbent are associated with the CO_2 mass transfer/adsorption kinetics, heat of adsorption, solid heat capacity and thermal conductivity, and thermal stability. On average, these parameters heavily affect the energy requirement for the solid-DAC. For instance, the kinetic influences the amount of material required for the DAC air contactor, the heat of adsorption and solid material physical properties the heat required for the regeneration, and finally, the thermal stability is directly connected to the maintenance and replacement rate of the adsorbent material.
- Some data on energy consumption and technoeconomic assessment from technology developers are available, but are based on smaller scale plants, so estimates for >10 000 t_{CO2}/year plants require using scaling factors.
- Adsorbent cost (driven by consumption/lifetime and price) is the most influential parameter on levelized costs of DAC (LCOD), but information is commercially sensitive. There is significant room for reductions in future adsorbent costs due to efficiency improvements and mass production of novel chemicals; however, new sorbents need demonstrating, so somewhat conservative cost reductions are assumed in most cases in the IEA report.
- The literature is particularly lacking in terms of future cost improvements, as estimates are based on learning rates from other industries, which may or may not be relevant for DAC.

Common DAC data uncertainties and availability:

- Some other parameters, such as maintenance and consumable prices have higher uncertainties,
- This section reported the main outcomes looking into independent technical reports and the most relevant literature on DAC techno economic assessment (TEA). We would like to remark that no knowledge and comments of the CO_2 purity and other species composition are reported. Thus, we do not have any certainty that the produced CO_2 from the DAC processes fulfil the Norther Lights specification. Noteworthy, the specification for oxygen is strict, less than 10 ppmv.
- CO_2 transport and storage costs are almost always excluded from DAC analysis in the literature. These are relatively well-established processes with reasonable certainty, however, costs are highly site dependent, so should be considered separately unless shared infrastructure is used.
- Scaling down liquid plant sizes to 100 000 t_{CO2}/y and scaling up solid plant sizes up to 1 mill. t_{CO2}/y require using generic scaling factors and significant assumptions, presenting uncertainties.
- Long term cost reductions are inherently difficult to predict since total DAC capacity to date is limited. This uncertainty is unlikely to be resolve until capacities reach at least several mega tons and the learning curve is confirmed, which may take until the 2030s.
- Land and water requirements can show wide ranges in the literature. Although not very influential on costs, these parameters may be better understood once several facilities are built and interactions between closely sited DAC plants are studied.

Table 3 – Key features of solid- and liquid-DAC technology approaches (table reproduced with permission from the International Energy Agency, Direct Air Capture – A key technology for net zero, IEA report, 2022, all rights reserved)

	Solid-based DAC	**Liquid-based DAC**
CO_2 separation device	Adsorbent	Liquid basic solvent
Overall[28] specific energy consumption [GJ/t_{CO2}]	7.2 – 9.5	5.5 – 8.8
Heat consumption [%]	75 – 80%	80 – 100%
Electricity consumption [%]	20 – 25%	0 – 20%
Regeneration temperature	80 – 100°C (maximum 120°C)	Around 900°C
Regeneration pressure	Vacuum (around 50 mbar)	Ambient
Capture capacity	Modular (50 000 t_{CO2}/year per unit)	Large-scale (0.5-1 mill. t_{CO2}/year)
Net water requirement [t_{H2O}/t_{CO2}]	-2.0 to none	0 – 50
Land requirement only DAC (1.0 Mt_{CO2}/y) [km^2/Mt_{CO2}]	1.2 – 1.7	0.4
LCA and carbon footprint [t_{CO2} emitted/t_{CO2} captured]	0.03 – 0.91	0.1 – 0.4
Cost of capture [USD/t_{CO2}]	Up to 540	Up to 340
Advantages	• Possible net water production (will be site dependent) • Less capital-intensive • Modular • Operation can rely on low-carbon energy only • Novel and therefore more likely to see costs reduction	• Less energy-intensive • Potential for fully electricity-driven DAC • Large-scale capture • Operation relies on commercial solvents • Technology adapted from existing commercial equipment
Trade-offs	• More energy intensive (heating of the sorbent) • Manual maintenance required for adsorbent replacement (low material life-time)	• Capital-intensive • Relies on natural gas combustion for the solvent regeneration (potential for full electrification in the future)

Notes: Land requirement excludes land use associated with electricity and heat generation. Life cycle emissions do not consider upstream emissions. Please note that the carbon intensity of the electricity supplied via the grid varies substantially by region/country. Net water requirements affected by regional factors such as air temperature and humidity, with solid-DAC technology potentially better suited to dry climates and liquid-DAC technology to humid climates. Sources: Madhu (2021) [60], Climeworks (2021) [76], Keith et al. (2018) [8], McQueen et al. (2021) [48], Fasihi et al. (2019) [71], Beuttler et al. (2019) [53], WRI (2021) [77].

[28] This value sums both electrical and thermal duties

<table>
<tr><td>Current Performance</td><td>
• Early DACCS projects in the 2020s are likely to range from ~$400-$700/net-tCO_2 stored (when global average solar PV costs are used) depending primarily on scale and type of technology.
• Costs drop to ~$350-$550/net-tCO_2 stored with low-cost renewables, therefore early plants are likely to be situated where renewable electricity is most affordable. Liquid DACCS plants get significantly more cost-effective with increasing size due to economies of scale. Solid DACCS costs scale more linearly with size and are likely to be the more cost-effective option for smaller plants (<100ktCO_2/year).
</td></tr>
<tr><td>Key Cost Influences</td><td>
• Liquid DACCS costs are most sensitive to upfront capital investment (Capex) and electricity prices. Due to the relatively balanced distribution of costs, most parameters are influential on LCODs, except for consumable prices including capture chemicals.
• Solid DACCS prices are most sensitive to adsorbent costs and future adsorbent performance improvements are the single most important factor which will determine cost-effectiveness of solid DACCS. Solid DACCS costs are also more sensitive to plant lifetime and may significantly suffer if lifetime is reduced.
</td></tr>
<tr><td>Cost Reduction</td><td>
• Significant cost reduction can be achieved in the future, with DACCS reaching ~$194-$230/net-tCO_2 for 1 MtCO_2/year NOAK plants (~2050), driven by reduced electricity prices, cost of capital and upfront capital investment. Costs are likely to be higher for smaller plants and further cost reduction potential exists for more ambitious renewables and adsorbent cost reduction, with solid technologies having more room for innovation learning as they utilise more novel chemical processes.
• Liquid DACCS further benefits from overall improvements in lifecycle emissions. Solid DACCS technologies experience further cost reduction through increases in plant lifetimes (from 10 to 25 years) and cost-performance improvements of adsorbents.
• CO_2 transport and storage costs are found to be ~6-15% of total LCODs and costs may be reduced by $20-$25/tCO_2 if plants use shared infrastructure.
• Energy costs are as much as 50% of long-term liquid DACCS costs. DACCS costs in the range of ~$150-$200/net-tCO_2 may be achieved in the long-term if very low-cost solar energy is used.
• Long-term costs are found to be significantly higher than the industry target of $100/t$CO_2$ captured, except under ambitious cost-performance assumptions and favourable conditions. These favourable conditions may come to exist but commenting on the size of the opportunity is difficult.
</td></tr>
<tr><td>Lifecycle Emissions</td><td>
• Emissions are primarily associated with the energy inputs (electricity and heat) and upstream methane emissions if natural gas is used in the process. Therefore, reducing the carbon intensity of energy sources is of paramount importance.
• The lifecycle emissions associated with DACCS range from 7-17% of the CO_2 captured for FOAK plants and 3-7% for NOAK plants (if low carbon energy is used).
</td></tr>
<tr><td>Energy Demand</td><td>
<table>
<tr><th></th><th>FOAK Liquid DACCS[89]</th><th>NOAK Liquid DACCS[89]</th><th>FOAK Solid DACCS</th><th>NOAK Solid DACCS</th></tr>
<tr><td>Thermal energy cons. (GJ/tCO_2)</td><td>6.8</td><td>0</td><td>10.8 (-)</td><td>4.9 (-)</td></tr>
<tr><td>Electrical energy cons. (GJ/tCO_2)</td><td>2.2 – 3.7</td><td>7.2 – 9</td><td>2.3 (6.6)</td><td>1.6 (3.6)</td></tr>
</table>
• Much of this data is sourced from companies developing DACCS systems. These are largely in line with those in the literature, with the slight exception of solid DACCS, where electricity consumption is at the higher end of the reported ranges in the literature, and the addition of the possibility of electricity-only solid DACCS systems. (Figures in brackets for solid DACCS are an electric-only configuration.)
</td></tr>
<tr><td>Uncertainties</td><td>
• Since no large-scale plant is built to date, inherent uncertainties on most parameters are high. The largest uncertainties requiring major assumptions are on capital costs, plant scaling factors, future cost reductions through learning, and solid adsorbent cost-performance dynamic.
</td></tr>
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Figure 19 – Key findings from TEA (picture reproduced with the permission from Element Energy's and IEAGHG report, Global Assessment of Direct Air Capture Costs, 2021)

DAC companies' estimates

Information on the DAC costs from company is quite fragmented. It is often impossible to determine the assumptions adopted in their TEAs. McQueen et al. [48] resumed the public information available from article, generally where key figures in the DAC start-up appear as authors, or from the companies' webpages where their advertise their own technologies providing some estimates on the energy requirements (Table 4).

Unfortunately, only Climeworks has already deployed its technology on industrial small-scale and provided some estimates. Climeworks levelized costs are more aligned with House et al. [28] and IEA reports [6,7] rather than other studies gathered in Table 1 which appear more optimistic on solid-DAC. Climeworks states that (with reference to the Orca plant, 4000 t/y) the current cost per captured CO_2 is around 500-600 USD/t_{CO2}. The Swiss company is confident to drop this value below 300 USD/t_{CO2} and the target is below 100 USD/t_{CO2} thanks to learning-by-doing by 2030 [63,64]. The costs drop rate according to the learning-by-doing is confirmed also in the literature [71].

Carbon Engineering would deliver its solution on large scale (larger than 500 000 t_{CO2}/y, thus, tens of times the current size of Climeworks and Global Thermostat scales), but their facilities with such a high capture rate are still under construction. Their estimates for the TEA come from theoretical studies and simulations [8]. For this reason, these values should be carefully considered, and an industrial validation is necessary before consolidating them. The estimates from Global Thermostat are quite optimistic if compared with international reports by IEA (Table 3) and international experts (Table 1-Table 2).

The reported estimates for the levelized cost and energy consumption (both thermal and electricity) are similar to the ones suggested by Kiani et al. [26] and depicted in Figure 20. This work is interesting since it provides a transparent TEA for MEA amino-acids DAC. MEA solutions are less basic than KOH/NaOH solutions; thus, it is reasonable to expect larger energy consumptions, thus, higher costs for capture CO_2 with regards to Carbon Engineering solution. Kiani simulated the DAC plant fixing the liquid-gas (L/G) ratio in the absorber to 2.54. This value is typical for carbon capture from flue gas in conventional absorbers. Due to the huge air volumetric flow, the corresponding liquid flow is large. High recycling ratio[29] (> 95%) allows to reduce the energy consumptions at the stripper regeneration because only 5% of a large aqueous solution undergoes regeneration.

[29] Recycling ratio is defined as the amount of rich solvent recycled to the absorption against the global liquid flow withdrawn from the bottom of the absorber. Recycle ratio larger than 95% means that only a maximum 5% of the rich solvent is regenerated in the stripper column. This configuration is adopted in the proposed DAC solution to avoid huge thermal duty for the regeneration since the rich solution is not as exhausted as in the case of the capture process from flue gas using 30% MEA solution in weight. The DAC plant proposed by Kiani et al. is a clear modification of the conventional CO_2 capture system where the absorber is like an evaporative column.

Table 4 – Public information on commercial DAC entities (table reproduced from McQueen et al., A review of direct air capture (DAC): scaling up commercial technologies and innovating for the future, 2021, Prog. Energy 3 032001 under Creative Commons Attribution License CC BY 4.0)

	Carbon Engineering [8,62,78,79]	**Climeworks** [53,63,72]	**Global Thermostat** [52,65,80]
Founding year	2009	2009	2010
Current scale [kt_{CO2}/y]	0.365 – 4.0	1.0	1.0
Thermal energy [GJ/t_{CO2}]	5.25	5.76	–[30]
Temperature for the regeneration [°C]	900	80 – 120	Preferably 105-120 but up to 130
Electricity requirement [kWh]	366	400	–[30]
Current costs [USD/t_{CO2}]	–	500 – 600	–[30]
Projected costs [USD/t_{CO2}]	168 – 232 FOAK 94 – 170[31] NOAK	Target of 200 – 300 within 5 years and 100 within 10 years[32]	–[30]
Past projects	Pilot plant in British Columbia with size 0.6 t/d	Goal to remove 225 mill. t_{CO2}/y by 2025	Pilot plant in Melano Park, CA capturing roughly 1000 t_{CO2}/y
Future projects	Industrial scale plant with Oxy Low Carbon Ventures capturing up to 1 mill. t_{CO2}/y slated to beginning construction in 2022		Two pilot scale plants with the capacity around 3-4000 t_{CO2}/y. Industrial scale plant construction with Exxon Mobil

Figure 20B reports the costs of the captured CO_2 and compares the estimates for other technologies. The mean MEA amino-acids DAC levelized cost[33] is aligned with what is reported by Climeworks. It is worth to note that the range provided in the article outlines that the minimum costs for MEA DAC is close to the Carbon Engineering estimate. The amino acids DAC costs is almost four times the Carbon Engineering even though the energy consumptions are only three and two times for the electricity and thermal input,

[30] Global Thermostat has not made any cost or energy estimates publicly and transparently available
[31] The cost range of 94–130 USD/t_{CO2} reflects scenario D from Keith et al. [8]. This scenario represents a system optimized for air-to-fuels, where hydrogen is produced via electrolysis which results in an oxygen by-product. This eliminates the need for an air separation unit as the oxygen is provided from electrolysis, additionally reducing electricity requirements for the DAC component of the system.
[32] These costs represent publicly stated cost targets for Climeworks from 2019

[33] Levelized cost of DAC (LCOD) expresses the cost estimates per ton of captured CO_2. In this way, the contrast among the different technologies is more robust and reliable since the costs are independent of the DAC facility capture capacity even though the economy of scale could benefit to liquid-DAC and to a lower extent to solid-DAC.

respectively. It is worth notifying that in the amino-acids DAC configuration the thermal energy input is not as low as the Carbon Engineering solution. Indeed, amino acids solutions are regenerated at around 110-120°C while the calciner requires at least 900°C. This simple reasoning may confirm that Carbon Engineering estimate is quite optimistic. The design of a high-temperature equipment (as the calciner in Carbon Engineering technology) is often challenging due to mechanical resistance of the construction materials and the thermal insulation. Special materials are adopted to build them. For these reasons, these units are quite expensive.

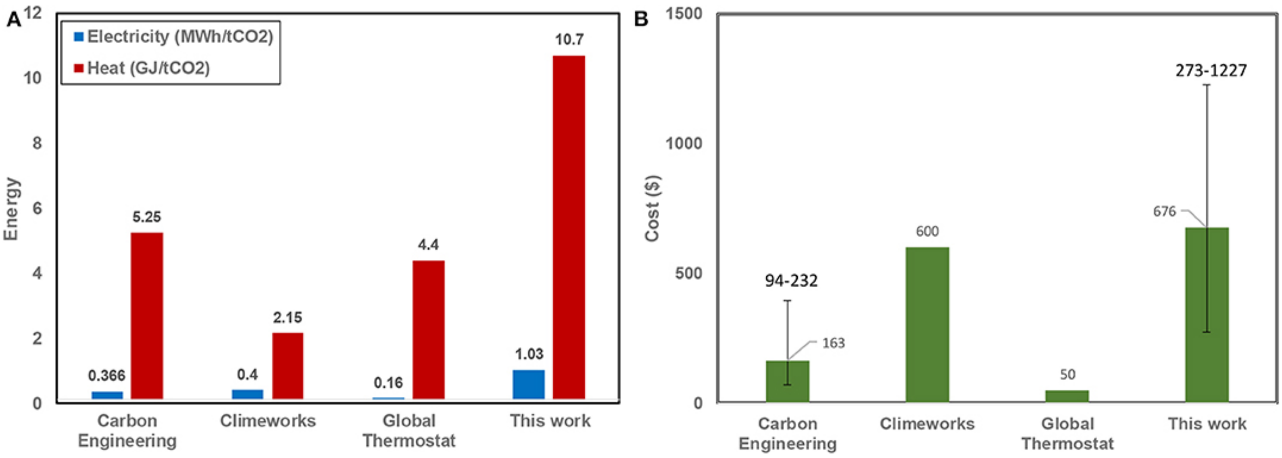

Figure 20 – (A) Energy consumption and (B) total cost reported in different studies for direct air capture processes. Note that \$50/tCO_2 reported by Global Thermostat was the cost that they anticipated to achieve. No information whether they have achieved this. Also, this work and Carbon Engineering's study reported a range for the cost of the process, based on various economic parameters. (Kiani et al., Techno-Economic Assessment for CO_2 Capture from Air Using a Conventional Liquid-Based Absorption Process., 2020, Front. Energy Res. 8:92. Doi: 10.3389/fenrg.2020.00092 under Creative Commons Attribution License CC BY)

It is noteworthy that the provided values for the energy consumptions are quite aligned with the independent estimates provided in the NASEM report [9]. The National Academy (US) suggests 0.74 – 1.7 GJ/t_{CO2} and 7.7 – 10.7 GJ/t_{CO2} for the energy and thermal input in liquid-DAC (Carbon Engineering estimates is 1.32 GJ/t_{CO2} for the electricity), whereas solid-DAC is expected to consume 0.55 – 1.1 GJ/t_{CO2} (electricity) and 3.4 – 4.8 GJ/t_{CO2} (heat). Climeworks and Global Thermostat identify 1.44 GJ/t_{CO2} and 0.58 GJ/t_{CO2} for the electricity, respectively.

Remarks

Chauvy and Dubois [81] report an exhaustive overview of the energy consumption (Figure 21) and the costs of the captured CO_2 currently and projected to 2030-2050 (Figure 22). Both plots show that experts TEA are not completely aligned and sometimes the discrepancies could be large. According to the experts, the electricity demand for DAC is around 430 ± 130 kWh/t_{CO2} and the thermal heat ranges regardless the technology 5600 ± 500 MJ/t_{CO2} (1.56 MWh/ t_{CO2}), regardless of the technology. The proposed values are comparable with those reported in NASEM report as already discussed except for the thermal energy (NASEM reports 770-10,700 MJ/t_{CO2}) for the Carbon Engineering solution. The discrepancy is less evident for the electricity requirement. This further corroborates what is previously discussed. DAC technology is at its infancy and accurate estimates are not available yet due to low deployment and industrial validation. The TEA published in the literature are based either on experimental data (mainly on lab-scale or lab prototype) or assumptions. Different assumption (for instance, only on the location influences the cost of the utilities such as electricity, cooling water, or waste heat availability) leads to different specific costs of the DAC.

The specific energy consumption deserves a more detailed analysis. It is not clear the reason behind the large discrepancies for the electricity usage even for the same technology (Figure 21A) while this is not verified for the thermal input (Figure 21B). Figure 21A shows that for the Carbon Engineering solution most of the TEA reported tend to underestimate the electricity. The opposite is observed for Climeworks. Probably, but this is a hypothesis, the confidence and knowledge of the technology and pieces of equipment installed in the two technologies may justify the opposite trend. Climeworks solution relies on the adsorption which is less industrially applied and conventional than absorption and thermal regeneration. Conversely, Carbon Engineering DAC involves conventional units[34] whose design and main features are well established.

Experts could have overestimated the solid-DAC specific consumption because they would have unintentionally kept a larger “safety” margin on their estimates due to an intrinsic lower confidence with novel technologies and equipment, whereas the higher confidence with industrially validated units may lower the perception of the uncertainties associated with Carbon Engineering. Still on the topic, modular solutions are less conventional than standard design. For instance, the oil and gas sector, and more in general chemical industry (with large volume production) benefit on (1) plants where each unit is tailored and designed for a fixed capacity, and (2) economy of scale. These two concepts do not perfectly fit the modularity that Climeworks is proposing. This introduces further unknowns and uncertainties on the technology costs and potential deployment.

Other aspects may further corroborate this hypothesis. Carbon Engineering technology considers conventional solvent (KOH/caustic solution and calcium hydroxide) which are commodities. Further, the thermodynamics involved in the CO_2 capture process has been already studied (conventional acid-base sequestration process, very similar to amine capture). Conversely, Climeworks module is patented, and the company discloses very little on the module it is testing. The capture mechanism via adsorption is specific to the novel adsorbent material the experts developed (amine-impregnated adsorbent, but nothing else is known). The R&D being carried out is trying to find an adsorbent with improved features and performance.

We cannot be sure that Lewatit (the first proposed and tested material) is still the adsorbent used in the Climeworks module. The uncertainties associated with the Climeworks module and more in general with the solid adsorption are higher. These aspects may have led to more conservative assumptions in the TEA assessment of the solid-DAC. As pointed out by Young et al. [75], at the current state the largest uncertainties in the design of adsorbent are the CO_2 mass transfer/adsorption kinetics, heat of adsorption,

[34] Slaker and pellet reactor are conventional units since they are used in pulp industry for the Kraft process

solid heat capacity and thermal conductivity, and thermal stability. These parameters heavily affect the energy requirement for the solid-DAC. Thus, if high uncertainties are associated with these dominant parameters, the higher uncertainties are reflected into the estimated costs per captured CO_2. This could also be reason why many experts are sceptical with the TEA of the Global Thermostat DAC. The specific cost (50 USD/t_{CO2}) is quite unrealistic despite the specific energy consumptions are in line with general indicators and competitors. The drop of the costs for DAC is aligned with IEA projections. Depending on the technology development and the support to the DAC deployment, the costs is expected to drop from 480 ± 100 €/t_{CO2} to around 140 €/t_{CO2}.

Finally, we would like to remark that the reviewed articles and technical reports have no knowledge and comments of the CO_2 purity and other species composition. Thus, <u>we do not have any certainty that the produced CO_2 from the DAC processes fulfils the Norther Lights specification</u>. The specification has very low values for water, 30 ppmv, and oxygen, 10 ppmv, which typically would need extra processing.

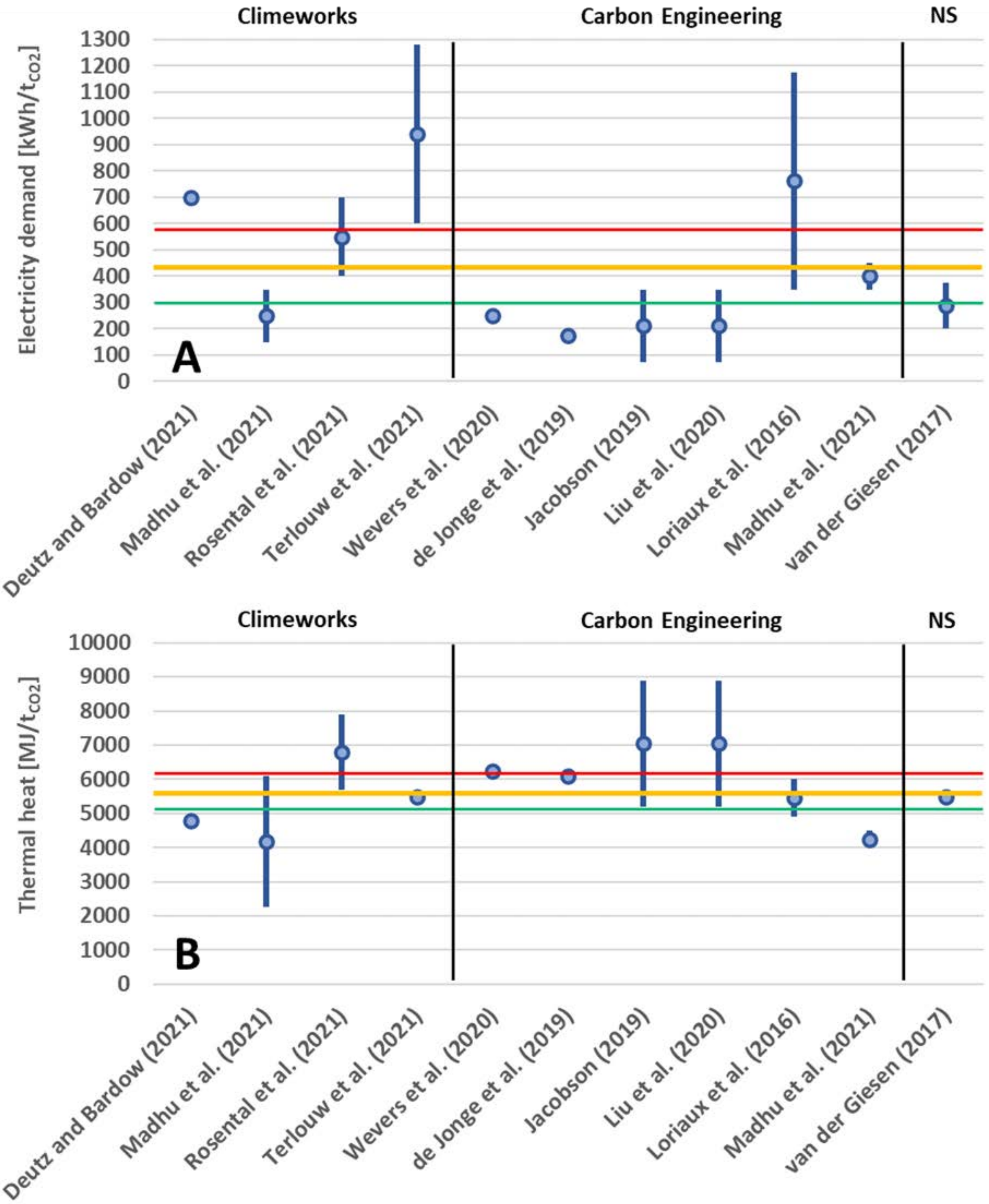

Figure 21 – Overview of the literature estimates for DAC energy consumption electricity (A) and thermal (B). The estimates are clustered according to the technology: Climeworks (solid adsorption) and Carbon Engineering (liquid solvent). Van der Giesen et al. (2017) have not specified the technology they analysed. The average value, average of the maximum (upper limits), and average of the minimum values (bottom limits) are highlighted the yellow, red, and green horizontal lines, respectively.

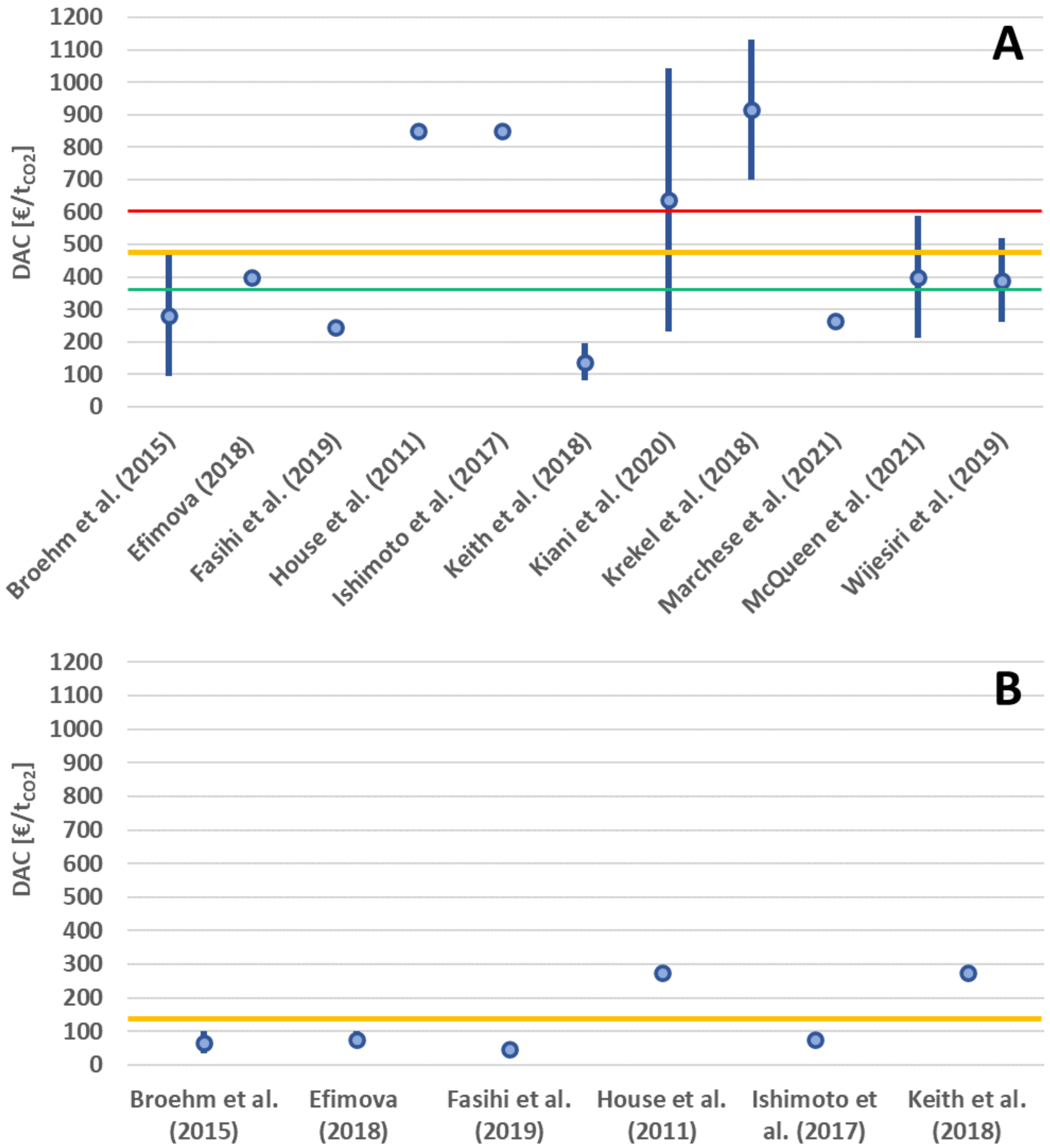

Figure 22 – Overview of the literature estimates for DAC costs currently (A) and projections to 2030-2050 (B). The average value, average of the maximum (upper limits), and average of the minimum values (bottom limits) are highlighted the yellow, red, and green horizontal lines, respectively.

5. DAC deployment and capacity

How many DAC facilities do we need?

Currently, 18 DAC plants are operative around the world (partially depicted in Figure 23) [82] and gathered in Table 6. Globally, DAC facilities account for almost 9000 t_{CO2}/y. The amount of captured CO_2 is negligible, compared to the global emissions in 2020 (36 Gt_{CO2}/y [1 Gt = 1 000 000 000 t]) and to the amount of CO_2 which should be recovered by 2100 (20-25 Gt_{CO2}/y) to cope with Paris Agreement 1.5, or 2°C temperature increment as stated in the UN report [83].

Considering the current emissions in Norway (49.1 mill. t_{CO2}/y [35]) it is possible to make some estimates. We assume capturing almost 30% of the yearly Norwegian emissions (capturing 15 mill. t_{CO2}/y). The estimates are gathered in Table 5 for both solid-based and liquid- DAC facilities. We used reference values for the land allocation and energy consumptions as in the main reports on the topics (IEA and NASEM) [6,7,9]. In addition, for the liquid-DAC we provide the estimates under three different scenarios: fully electric, natural gas based, and hybrid. In the fully electric scenario, we assumed that the calcination is performed by burning hydrogen, thus, the thermal demand of the DAC process is covered using green hydrogen produced through electrolysis which consumed electricity from the national grid. In the so-called natural gas-based scenario, the DAC plant relies exclusively on the natural gas, thus, a gas turbine satisfies the electrical demand, and the combustion of the natural gas provides the thermal heat in the calciner. In other words, both electrical and thermal request are satisfied through natural gas combustion with CCS. Finally, the hybrid case considers an intermediate condition where the national electricity grid covers the electrical energy demand, while combustion of natural gas still covers the thermal supply.

[35] Source - https://www.ssb.no/natur-og-miljo/forurensning-og-klima/statistikk/utslipp-til-luft/artikler/klimagassutslippene-gikk-ned-0-3-prosent-i-2021

Table 5 – Case study results for 15 million t_{CO2}/y (approximately 30% of yearly emissions) capture in Norway

<table>
<tr><th>Technology and gross plant capacity</th><th>How many plants?</th><th>Land allocation (only DAC facility)</th><th>Electricity consumptions</th><th>Thermal energy consumption</th><th>Notes</th></tr>
<tr><td>Solid-based DAC
(4 kt_{CO2}/y)</td><td>3750</td><td rowspan="2">22.5 km^2</td><td rowspan="2">21.8 – 38.4 TWh_{el}/y
(13.9 – 24.4% of the Norwegian electricity production[36])</td><td rowspan="2">–</td><td>Based on the current maximum capacity of solid-DAC</td></tr>
<tr><td>Solid-based DAC
(36 kt_{CO2}/y)</td><td>417</td><td>Scale-up scenario (plant under construction). The range in the electricity consumptions accounts for different adsorbents and system efficiency.</td></tr>
<tr><td>Liquid-based
(1 Mt_{CO2}/y = 1 000 000 t/y)
Fully electric</td><td rowspan="3">15</td><td rowspan="3">6-8 km^2</td><td>Baseline
3.75 TWh_{el}/y

Electrolysis
59.13 TWh_{el}/y

(62.88 TWh_{el}/y corresponds to 40% of the Norwegian electricity production)</td><td>–</td><td>Overall electricity consumption is 62.88 TWh_{el}/y. Alkaline electrolyser provides the hydrogen to cover the thermal demand and reference values for 1 Mt_{CO2}/y scale are in NASEM report. The land allocation does not account for the electrolysers land footprint. <u>Baseline</u> includes all the electricity request for air fans, pumps, and any pieces of equipment different from the calciner.</td></tr>
<tr><td>Liquid-based
(1 Mt_{CO2}/y)
Natural gas-based</td><td>–</td><td>37.77 TWh_{th}/y
(4050 million Sm^3 – 3.32% of the natural gas export[37])</td><td>The DAC facilities will consume around 4050 million Sm^3 yearly of natural gas which correspond to 3.32% of the Norwegian natural gas export</td></tr>
<tr><td>Liquid-based
(1 Mt_{CO2}/y)
Hybrid</td><td>3.75 TWh_{el}/y
(2.4% of the Norwegian electricity production)</td><td>25.70 TWh_{th}/y
(2755 million Sm^3)</td><td>The natural gas consumption is around 2755 million Sm^3 of natural gas which correspond to 2.26% of the Norwegian natural gas export</td></tr>
</table>

[36] Reference value 157.113 TWh in 2021 – source Electricity (ssb.no)
[37] Reference value 122 billion of Sm^3 of natural gas export – source Exports of Norwegian oil and gas - Norwegianpetroleum.no (norskpetroleum.no)

What is the current state of DAC deployment?

Overview of current deployment and planned pilot/facilities

Climeworks is the most active company, and it has already 15 DAC facilities operative and distributed mainly in Europe, Table 6. Climeworks has a clear advantage in the deployment of its technology over the other DAC EPC because of the easy scalability of the adsorption module. Currently, the operative DAC facilities cover small scale applications (i.e., less than 1 mill. t_{CO2}/y). The largest operative industrial DAC pilot plant is Orca (4000 t_{CO2}/y) in Iceland at Hillesheidi [84]. At the Orca plant the capture CO_2 is mineralized (CarbFix project[38]). Table 6 gives an overview of all the operative DAC plants and the final disposal of the captured CO_2. In June 2022, Climeworks started building the Mammoth plant whose capacity is expected to be 36 000 t_{CO2}/y [85].

Conversely to Climeworks (modular technology), Carbon Engineering technology benefits from the economy of scale, thus, it aims at building large-scale DAC plant (larger than 1 mill. t_{CO2}/y) to reduce the levelized costs of the captured CO_2. However, the scale-up from the small-scale to large industrial applications is time demanding. For this reason, Carbon Engineering appears less active in the building and deployment of its adsorption module. More recently (June 2022), 1PointFive (OXY)[39] and Carbon Engineering announced direct air capture deployment approach to enable global role out of plants. Michael Avery, the president of 1PointFive, stated that his company is committed to delivering large-scale DAC solutions to remove carbon dioxide from the atmosphere and help achieve the goals of the Paris Agreement. The agreement between OXY and Carbon Engineering will lead to the construction of 70 DAC large-scale facilities (each 1 mill. t_{CO2}/y) by 2035. According to OXY CEO, their first plant will capture up to 0.50 mill. t_{CO2}/y of CO2. This plant will be 120 times bigger than the other largest DAC, Climeworks' Mammoth site [86,87]. Global Thermostat is slowly deploying its modules. The most relevant achievements are the agreements signing with Exxon Mobil and HIF[40]. Exxon Mobil asked for the commissioning of two DAC pilot plants in 2020 and it will contribute to advance the scale-up of Global Thermostat capture technology [88]. The agreement has been renewed recently (April 2022) [89]. In April 2021 Global Thermostat signed a contract with HIF to supply DAC equipment to the Haru Oni eFuels pilot plant in Chile. HIF announced the financial support from the German Government for its Haru Oni pilot plant with the participation of Porsche, Siemens Energy, Enel Green Power, ENAP, and ExxonMobil. The DAC plant is designed to capture around 2000 k_{CO2}/y [90].

Sovacool et al. [91] propose a more complete table reporting a full historical development of DAC technologies in terms of deployment. For sake of completeness, we list only the accomplished and planned DAC facilities for Carbon Engineering, Climeworks, Global Thermostat, and Verdox (Table 7). We neglect all the other technologies since technical details of the DAC system and novelty are missing. Merging the information provided in the literature, it emerges that DAC is a novel technology, and its deployment is the business for a few companies founded in 2010. Other start-ups are entering the market, but they prefer to cover niches of market where the most established companies (Carbon Engineering, Climeworks, and Global Thermostat) do not provide services or their technologies are not suitable for specific application,

[38] Climeworks begins operations of Orca, the world's largest direct air capture and CO_2 storage plant and Direct Air Capture - Carbfix
[39] 1PointFive is a subsidiary of Occidental's (NYSE: OXY)
[40] HIF is an affiliate of Andes Mining and Energy (AME[Chile]). HIF's mission is to combat climate change through the substitution of fossil-based petroleum products with carbon neutral eFuels. HIF's initial production facilities for this decarbonization initiative are based in Magallanes, Chile, with similar projects under development in the United States and Australia. More info at http://www.hif.cl/en

for instance, urban capture and greenhouse enhanced culture. Currently, the deployment of DAC facilities is limited and mainly located in Europa and less intensively in the North America.

Most of the planned plants (after 2021) are mainly situated in US and UK. Canada has already attracted DAC deployment since 2015 and now the Canadian government is intensifying its financial assistance to CCUS (including DAC) technologies. A new plant (Mammoth, capacity 36 000 t_{CO2}/y) is also planned in Iceland. Two of the main DAC companies (Carbon Engineering and Climeworks) and the more recent start-up Verdox seem to be interested in developing and deploying their own technology in Norway. The planned activities are just pre-feasibility studies, preliminary design for DAC facilities or long-term projects.

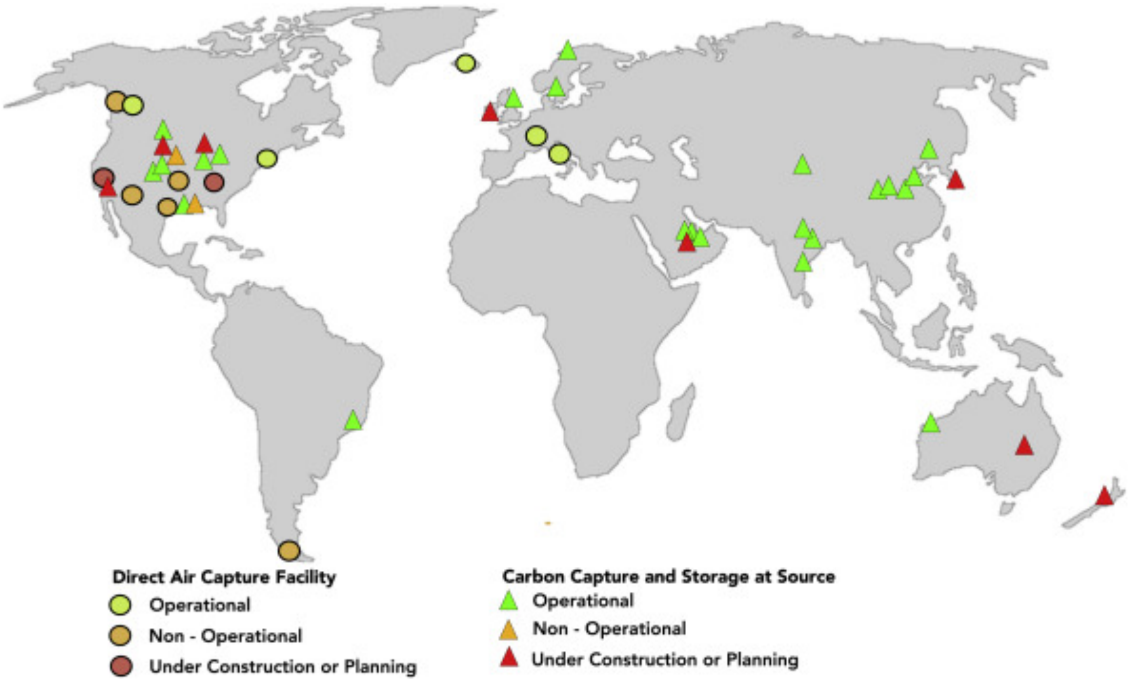

Figure 23 – Non-exhaustive map of the CCS and DAC facilities deployment and locations (picture reproduced from Ozkan et al., Current status and pillars of direct air capture technologies, 2022, iScience, 25(4), https://doi.org/10.1016/j.isci.2022.103990 under Creative Commons Attribution License CC BY-NC-ND)

Table 6 – Operative DAC facilities deployment (updated to April 2022) using data coming from IEA report [7]

Company	Country	Sector	CO_2 disposal	Start-up year	CO_2 capture capacity [kt_{CO2}/y]
Global Thermostat	United States	R&D	Unknown	2010	0.500
Global Thermostat	United States	R&D	Unknown	2013	1.000
Climeworks	Germany	Customer R&D	Use	2015	0.001
Carbon Engineering	Canada	Power-to-X	Use	2015	Up to 0.365
Climeworks	Switzerland	Power-to-X	Use	2016	0.050
Climeworks	Switzerland	Greenhouse fertilisation	Use	2017	0.900
Climeworks	Iceland	CO_2 removal	Storage	2017	0.050
Climeworks	Switzerland	Beverage carbonation	Use	2018	0.600
Climeworks	Switzerland	Power-to-X	Use	2018	0.003
Climeworks	Italy	Power-to-X	Use	2018	0.150
Climeworks	Germany	Power-to-X	Use	2019	0.003
Climeworks	Netherlands	Power-to-X	Use	2019	0.003
Climeworks	Germany	Power-to-X	Use	2019	0.003
Climeworks	Germany	Power-to-X	Use	2019	0.050
Climeworks	Germany	Power-to-X	Use	2020	0.050
Climeworks	Germany	Power-to-X	Use	2020	0.003
Climeworks	Germany	Power-to-X	Use	2020	0.003
Climeworks	Iceland	CO_2 removal	Storage	2021	4.000

Table 7 – Status of key and upcoming Direct Air Capture technology providers updated to 2022 (table partially reproduced from Sovacool et al., Climate policy for a net-zero future: ten recommendations for Direct Air Capture, 2022, Environ. Res. Lett. 17 074014 Creative Commons Attribution License CC BY 4.0)

	Project	Location	Start	Capacity and status	Notes
Carbon Engineering (liquid absorption)		Canada	2015	1 t_{CO2}/day (8.5 – 9 kt_{CO2}/y)	
		Canada	2017	1 t_{CO2}/day (8.5 – 9 kt_{CO2}/y)	Expansion of the initial pilot plant with new modules for pilot demonstration of synthesizing captured CO2 into fuels, up to ~1 barrel/d (159 litres of fuel)
		USA		Design and engineering phase for 1 Mt_{CO2}/y for commercial plant	Currently planning with partner in the USA to start construction in 2022 with no known date of planned
		Canada	After 2026	Feasibility study for 100 million litres fuel per year	If feasibility is given, construction is supposed to begin in 2023, operation roughly three years later
		Norway		Design phase for DAC plants removing 0.5-1 Mt_{CO2}/y	Cooperation with partners in Norway and start of design phase announced end of 2021, no further info yet
	Dreamcatcher	UK	2026	Preliminary design and engineering phase for DAC plant removing 0.5-1 Mt_{CO2}/y	
	AtmosFUEL	UK	2030	Feasibility study for 100 million litres of fuels per year	Start of operation planned for the end of the decade
Climeworks (adsorption)	Capricorn	Switzerland	2017	Commercial operation at up to 900 t_{CO2}/y	Captured CO2 is fed into nearby greenhouse. Regeneration at around 100°C, waste heat used for regeneration, modular approach
	Artic Fox	Iceland	2017	Proof of technology at up to 50 t_{CO2}/y	Proof-of-technology DAC pilot in cooperation with Carbfix. Regeneration at 80 – 100°C, geothermal heat used for regeneration.
	STORE&GO	Italy	2018	Proof of technology at up to 150 t_{CO2}/y	Research plant for power-to-gas proof of technology, running for 15 months. Project has ended
	Kopernicus P2X	Germany	2019	Proof of technology at up to 10 liters fuel per day	Single module used for the first step of power-to-liquid research. Regeneration at 80 – 100°C
	NECOC	Germany	2020	Proof of technology for DAC to carbon black plant	
	Orca	Iceland	2021	Proof of technology at up to 4 kt_{CO2}/y	DAC plant in cooperation with Carbfix. Regeneration at 80 – 100°C, geothermal heat used for regeneration, modular approach.
	Zenid	Netherlands		Preliminary design and engineering for 1000	Based on 2019 feasibility study, a proof-of-technology plant is planned. Current phase announced in 2021, no further update since.

				liters of aviation fuel per day	
	Mammoth	Iceland		Upgrade and deployment of the technology on 36 kt_{CO2}/y	DAC facility under construction (2021). This plant represents a demonstratable step in our ambitious scale-up plan: multi-megaton capacity by 2030 and being on track to gigaton capacity by 2050
		Norway		Design and engineering phase for 12.5 million litres aviation fuel per year plant	Part of the Norsk e-Fuel consortium. Construction start is planned for 2023, increase of production by 2026 to 25 million litres
Global Thermostat (adsorption)		USA	2010 - 2013	Proof of the technology	Menlo Park (California) plant capacity 10 kt_{CO2}/y
		USA	2021	Design and engineering phase for 100 kt_{CO2}/y	Developed by Black & Veach with global Thermostat DAC technology, to be used in Texas, Alabama, and Illinois. No date for start of construction or carbon capture. Fossil fuels supply thermal energy
	Haro Oni	Chile	2022	Construction phase of Power-to-liquid demonstration plants, capturing up to 2 kt_{CO2}/y	Demonstration plant by Highly Innovative Fuels for planned 230 kt_{CO2}/y Power-to-Liquid plant, planned to be operational in 2025 using wind energy.
Verdox (electro-swing adsorption, ESA)		**Norway**	2030	Design and engineering phase for flue gas	Technology is meant to work with flue and ambient gas, currently focused on aluminum smelter exhaust, planning for industrial scale by 2030. No thermal energy needed.

Policies to support DAC deployment in other countries

Recently, the **US** Government through Department of Energy (DoE) launched a series of economic package to support CCUS and DAC solutions. US Department of Energy has chosen this target for the Carbon Negative Shot, launched in November 2021, and aiming to projects to bring the cost of DAC below USD 100/t_{CO2} in a decade. Capture costs below 200-250 USD/t_{CO2} could already be commercially attractive in the United States where facilities are able to access the California LCFS credits (around 200 USD/t_{CO2}) together with tax credits such as the 45Q (50 USD/t_{CO2}). The plan includes a strong detaxation of DAC infrastructures to favour its deployment. The measures also involved the expansion and strengthening of the renewables energy grid and distribution [92–94].

Also, **Canada** opens to the DAC and the several districts can independently manage and regulate the legislation and favour DAC deployment. Canada also financed several research projects on DAC technologies [95–97]. In **UK**, the government intends to finance DAC deployment to achieve zero-emissions by 2050. The DAC has been included as strategic technology to pursue this ambitious target [98,99]. These strategies could change the global distribution of the DAC facilities and these first packages of economic measures also impacted on the planned DAC plants distribution.

Table 8 lists the main legislations and policies adopted around the world to support DAC deployment and negative emissions technologies (NET). Alberta state in Canada was the region in the world to promote CCUS and to adopt specific laws to convey and spread environmental policies. An increase in the laws to support these technologies has been registered in the last three years. More details are reported in the links in the footnotes to Table 8.

Table 8 – Policies to favour DAC facilities deployment and negative emissions technologies (NET) based on data available on the IEA webpage (Direct Air Capture – Analysis – IEA)

Policy	Country	Year	Status	Jurisdiction
Investment tax credit for carbon capture, utilization, and storage (CCUS)[41]	Canada	2022	Planned	National
CO_2 avoidance and use in raw material industries[42]	Germany	2021	In force	National
DOE funding for DAC and storage[43]	US	2021	In force	National
Federal government – South Australian Energy and Emissions Reduction Deal[44]	Australia	2021	In force	National
Investment in Direct Air Capture CO2[45]	US	2021	In force	National
SCALE Act (Storing CO2 and Lowering Emissions Act)[46]	US	2021	Planned	National
Australian Technology Investment Roadmap[47]	Australia	2020	In force	National
Energy Act of 2020 (CCUS provisions)[48]	US	2020	In force	National
Ten Point Plan for a Green Industrial Revolution – Point 10: Green Finance and Innovation[49]	UK	2020	In force	National
UK Plan for Jobs – Direct Air Capture[50]	UK	2020	In force	National
The Utilizing Significant Emissions with Innovative Technologies (USE IT) Act[51]	US	2019	In force	National
Section 45Q Credit for Carbon Oxide Sequestration[52]	US	2008	In force	National
(Alberta) Alberta Innovates' Cleaner Hydrocarbon Production Program[53]	Canada	2008	In force	Provincial

[41] https://www.iea.org/policies/13346-investment-tax-credit-for-carbon-capture-utilisation-and-storage-ccus
[42] https://www.iea.org/policies/13194-co2-avoidance-and-use-in-raw-material-industries
[43] https://www.iea.org/policies/14406-doe-funding-for-direct-air-capture-dac-and-storage
[44] https://www.iea.org/policies/14406-doe-funding-for-direct-air-capture-dac-and-storage
[45] https://www.iea.org/policies/13070-investment-in-direct-air-capture-co2
[46] https://www.iea.org/policies/13193-scale-act-storing-co2-and-lowering-emissions-act
[47] https://www.iea.org/policies/12123-australian-technology-investment-roadmap
[48] Energy Act of 2020 (CCUS provisions) – Policies - IEA
[49] Ten Point Plan for a Green Industrial Revolution - Point 10: Green Finance and Innovation – Policies - IEA
[50] UK Plan for Jobs - Direct Air Capture – Policies - IEA
[51] The Utilizing Significant Emissions with Innovative Technologies (USE IT) Act – Policies - IEA
[52] Section 45Q Credit for Carbon Oxide Sequestration – Policies - IEA
[53] (Alberta) Alberta Innovates' Cleaner Hydrocarbon Production Program – Policies - IEA

Funded projects and governmental support to research

DAC technology is acquiring attention and many funded projects are emerging for several millions (Table 9). Figure 24 focuses on the Europe situation with a detail on the Horizon program.

Table 9 – Major publicly funded DAC initiatives by region (table reproduced with permission from the International Energy Agency, Direct Air Capture – A key technology for net zero, IEA report, 2022, all rights reserved)

Country/area	Programme/instrument	Description
Canada	Climate Action and Awareness Fund[54]	The fund is investing CAD (Canadian Dollar) 206 million (USD 164 million) to support projects that will reduce Canada's GHG emissions, including efforts to understand the potential for, and implications of, carbon removal technologies including DAC.
	Net Zero Accelerator[55]	Part of the Strategic Innovation Fund, this initiative was announced in December 2020 and further enhanced by Canada's Budget 2021 to provide a total of CAD 8 billion (USD 6.4 billion) over seven years to support the decarbonisation of the industrial sector. DAC with CO_2 use is eligible as a climate-neutral CO_2 feedstock to produce low-carbon products.
	Clean Fuel Standard[56]	The standard will require liquid fuel suppliers to gradually reduce the carbon intensity of the fuels they produce and sell. Low-carbon-intensity fuels include those made from sustainably sourced biomass and DAC.
	Budget 2021[57]	The budget included CAD 319 million (USD 254 million) over seven years for Natural Resources Canada to fund RD&D to improve the commercial viability of CCUS technologies, including DAC.
EU	Horizon Europe (Figure 24)	DAC projects are eligible for support under Horizon Europe, the main EU funding programme for research and innovation, with a total budget across all areas of EUR 95.5 billion (around USD 113 billion).
	Innovation Fund	The EUR 10 billion (USD 11.8 billion) fund was launched in 2020 to support innovation in low-carbon technologies and processes, including CCUS and DAC
	Communication on Sustainable Carbon Cycles[58]	The communication, released in December 2021, sets out a strategy to increase removals of carbon from the atmosphere. It suggests that 5 Mt of CO_2 should be removed annually by 2030.
UK	DAC and GHG Removal Competition[59]	This competition, announced in 2020, will provide funding for technologies that enable the removal of GHGs from the atmosphere. Total budget is up to GBP (Greit Britain Pounds) 100 million (USD 137 million).
	Net Zero Strategy[60]	The strategy identifies a need for 75-81 Mt_{CO2} of engineered carbon removals via DAC and BECCS by 2050. DAC may also benefit from announced funding of GBP 180 million (USD 248 million) to support production of sustainable aviation fuels.

[54] https://www.canada.ca/en/services/environment/weather/climatechange/funding-programs/climate-action-awareness-fund.html
[55] https://ised-isde.canada.ca/site/strategic-innovation-fund/en/net-zero-accelerator-initiative
[56] https://www.canada.ca/en/environment-climate-change/services/managing-pollution/energy-production/fuel-regulations/clean-fuel-regulations.html
[57] https://www.budget.gc.ca/2021/home-accueil-en.html
[58] https://ec.europa.eu/commission/presscorner/detail/en/ip_21_6687
[59] https://www.gov.uk/government/publications/direct-air-capture-and-other-greenhouse-gas-removal-technologies-competition
[60] https://www.gov.uk/government/publications/net-zero-strategy

United States	45Q tax credit[61]	This tax credit (introduced in 2008 and expanded in 2018) provides USD 35 per ton[62] of CO_2 used in enhanced oil recovery and USD 50 per ton of CO_2 stored. The credit is available for DAC only if the capture capacity of the plant is above 100 000 t_{CO2}/year. There are a number of proposals to increase the value of the 45Q tax credit, including in the Build Back Better Act, which would provide USD 180/t_{CO2} for DAC.
	California Low Carbon Fuel Standard[63]	DAC projects anywhere in the world are eligible to receive LCFS credits, provided the projects meet the requirements of the Carbon Capture and Sequestration Protocol (including 100 years of storage monitoring). The LCFS credits traded at an average of around USD 200/tCO2 in 2020.
	Infrastructure Investment and Jobs Act[64]	Almost USD 12 billion in CCUS support was included in this act, which was enacted in November 2021. This includes USD 3.5 billion in funding to establish four DAC hubs (1 MtCO2 per year and above) and related transport and storage infrastructure. DAC projects are also eligible for additional CCUS funding support included in the act of around USD 0.5 billion. A DAC Prize programme was also fully funded by the infrastructure package, with USD 100 million for commercial-scale projects and USD 15 million for pre-commercial projects.
	Carbon Negative Shot[65]	This was announced during COP26 in November 2021 as a call for innovation in technologies and approaches that will remove CO2 from the atmosphere and durably store it at meaningful scales for less than USD 100/ton of CO_2-equivalent, including DAC.
	DOE funding programmes[66]	Multiple funding programmes specifically for DAC were announced in March 2020 (USD 22 million), January 2021 (USD 15 million), March 2021 (USD 24 million) and October 2021 (USD 14.5 million).
Japan	Moonshot Goal 4[67]	The Moonshot Goal 4 (a subset of the Moonshot R&D Program, launched in 2019 with a total budget of YEN 100 billion [USD 1 billion]) focuses on “the realisation of a sustainable resource circulation to recover the global environment by 2050”. In order to reach this goal, the Moonshot Goal 4 includes R&D funding of YEN 20 billion (USD 200 million) for multiple innovative technologies, including DAC.

[61] https://www.congress.gov/bill/115th-congress/house-bill/1892?q=%7B%22search%22%3A%5B%2245q%22%2C%2245q%22%5D%7D&r=2&s=2
[62] Metric tons (tonne) – conversion is 1 tonne = 1.1 ton (1,100 kg)
[63] https://ww2.arb.ca.gov/our-work/programs/low-carbon-fuel-standard
[64] https://www.congress.gov/bill/117th-congress/house-bill/3684
[65] https://www.energy.gov/fecm/carbon-negative-shot
[66] https://www.energy.gov/funding-financing
[67] https://www.nedo.go.jp/english/news/ZZCA_100007.html

	Celbicon	Carbfix and Carbfix 2	STORE&GO	NEGEM
Duration	2016-2019	2011-2021	2016-2020	2020-2024
Focus	CO_2 to chemicals (PHA bioplastic, methane)	CO_2 removal via mineralisation in basalt formation	Renewable power to gas (methane)	Techno-economic and social assessment of CO_2 removal
Funding sources	EU H2020, European Science Foundation, Austrian government Vienna Research Group for Young Investigators	EU FP7, EU H2020, US DOE, the Nordic Council of Ministers, GEORG	EU H2020, Swiss government	EU H2020
Total funding (EUR million)	6.2	3.8	28	5.8
Funding distribution	13% / 87%	15% / 85%	36% / 64%	100%

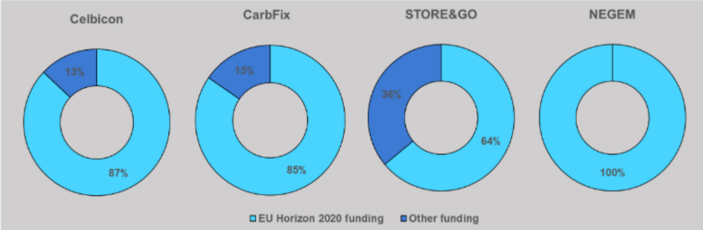

Figure 24 – Selected DAC projects that received public funding in Europe (table reproduced with permission from the International Energy Agency, Direct Air Capture – A key technology for net zero, IEA report, 2022, all rights reserved)

Remarks and final considerations

The numbers (provided in chapter "How many DAC facilities do we need?") depict the urgency of negative emissions technologies (NETs) deployment. Nevertheless, Ozkan [82] and Sendi [51] neglect some key points:

1. they assumed that the DAC technologies are close to industrial deployment but they neglect the need for further piloting to reach TRL-11 (see the section about Technology Readiness Level (TRL)) and specific policies,
2. they are not considering the supply chain which should be created for both DAC (thousands), materials production, and energy valleys construction (terawatt of renewables),
3. in their models/estimates they neglect the time needed to build DAC facilities (including the "energy farm") and establish a new energy grid system to supply the required energy, and
4. the location, probably the most important features to be accounted.

Further, for bullet point (3), large-size plant (e.g. Carbon Engineering) could take a couple of years before it is operational. Such large-scale DAC could really help to reach the target of 20 Gt_{CO2}/y capture rate. Point (1) is remarked in Figure 25. Indeed, the data available in the literature show that all the DAC companies are relatively far from the ideal large-scale target of 1 mill. t_{CO2}/y (even though large solid-DAC is designed for annual capture rate 100-400 000 t_{CO2}/y [85]). Carbon Engineering should validate a large-size plant by 2026 (just planned, not confirmed). Global Thermostat aims at reaching large-scale DAC facilities by 2025 (Figure 25B).

The immediate concern is whether the DAC sector could be able to catch up the timetable and expectations to contribute as NET to the climate change mitigation. It is noteworthy that what global DAC capture capacity of 10 Gt_{CO2}/y and 20 Gt_{CO2}/y corresponding to 33% and 67% of the current global emissions, respectively, seems to be unrealistic and unfeasible due to several factors: renewable energy supply and distribution, DAC capacity and TRL suitable for stable operation and global deployment, supply chain related to DAC facilities building (materials), but also policies to favour its development among the others. Answering to such a question is complex. Currently, DAC should be considered as a technology in its infancy, at least regarding implementation at industrial level. This is enough to state that it is complex and almost impossible to project the future role, contribution, and impact of DAC to climate change technologies. For sure, only large-scale DAC facilities or an extensive distribution of the DAC sites will benefit to CO_2 emissions reduction and control, but this will require the consumption of a huge amount of material, probably natural resources, and land for both the DAC and the renewable energy farm. Anyhow, the benefits should outweigh the controversial aspects of DAC. Nevertheless, the LCA of DAC processes needs more information and details that are missing currently. Thus, the final assessment of DAC is postponed until the technology will be mature enough.

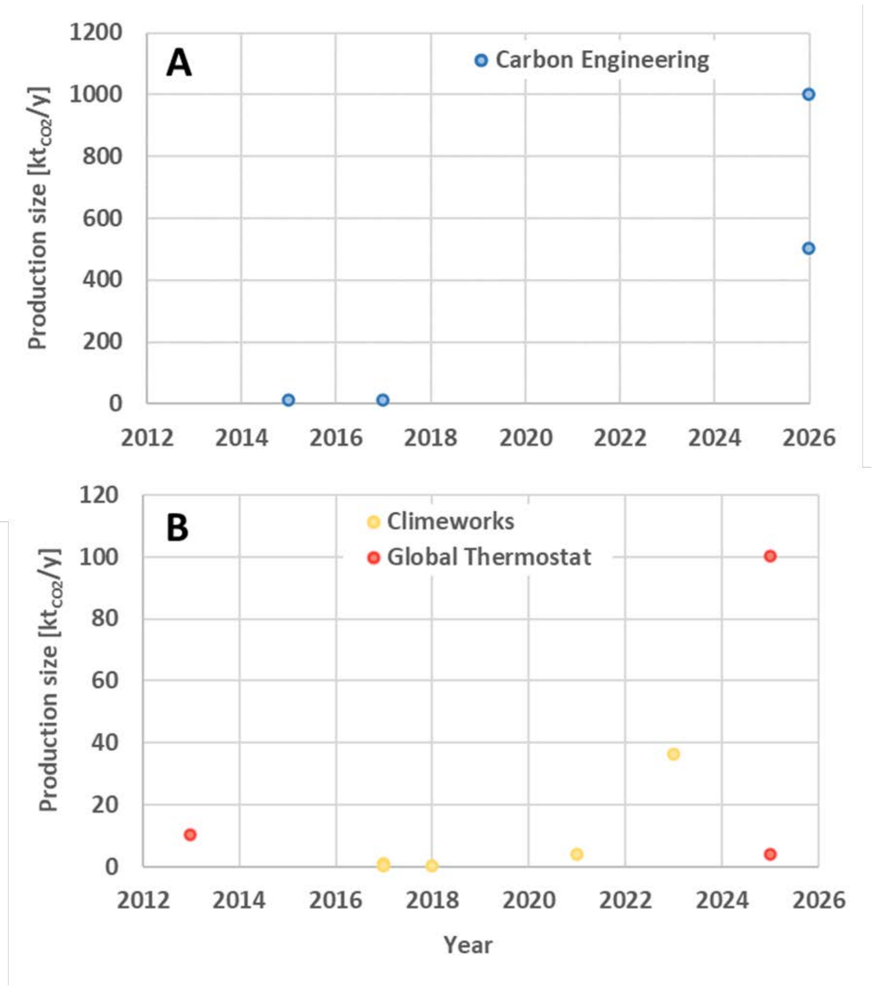

Figure 25 – Production size for pilot plants and planned DAC facilities for Carbon Engineering (A), Climeworks and Global Thermostat (B) using data or information gathered in Table 10

6. General features of DAC facilities and the best location

To assess the global impact and the best location for a DAC facility, it is important to fully know and understand the chemical process and have specific data related to the process itself. So far, this report dealt with the energy consumptions and the different technologies available either on the market or still under development. The previous part neglected other elements which are relevant. **Natural resources consumption** and **land use** are features to be accounted for. In addition, the **environmental/climate conditions** (temperature and humidity) and the presence of relevant/shared **infrastructure** (pipeline, storage sites, and auxiliary units/instrumentation) influence the capture efficiency and the costs, respectively. For this reason, the selection of the best location is a complex procedure which should consider a wide range of factors. **Public perception** may also be an issue. Nevertheless, since DAC technology is still at an early stage, it is worth also considering the technology readiness level (TRL) since the projected mega- and gigatons scale will require stable operation and deployment on a global scale. Currently, only a few DAC technologies have been validated for small-scale applications. The stability under long-time operation, maintenance, scale-up for the commercialization, and the "predictable growth", as suggested by IEA, are still under investigation.

Resources and material consumptions

Water consumptions

DAC facility operation is associated with either water release or consumption (water from an external source). This aspect is emphasized only in international reports while is neglected in articles both on LCA and TEA [6,7,9]. A general statement, solid-DAC could release water, while liquid-DAC must integrate the water it loses in the absorber (air contactor) and in the slaker. The water loss or release depends on the relative humidity and temperature of a given location. As a rule of thumb, the water losses are lower for humid and colder environments. Liquid-DAC can require 2-8 kg_{H2O}/kg_{CO2} water make-up to offset the losses to environment. According to Fasihi, the water unbalance could be more dramatic and liquid-DAC may consume up to 50 kg_{H2O}/kg_{CO2} [71]. Keith suggests some improvement to Carbon Engineering technology to reduce the water make-up. Conversely, solid-DAC releases water to the environment (i.e., condensates the air humidity). In this case, the estimates for the water are quite broad (0.8-2 kg_{H2O}/kg_{CO2} released and a suggested average value around 1.6 kg_{H2O}/kg_{CO2} in IEA and NASEM report, whereas IEAGHG quotes 1.6-12 kg_{H2O}/kg_{CO2} consumed not released in contrast to other works). Note that the present estimates of the water demand refer to only DAC capture section. Looking at the full scale, DAC supply chain operation (thus, including the sequestration- or, alternatively, mineralization) would require a higher water use. For instance, the Orca DAC plant in Iceland operated by Climeworks stores the captured CO_2 in basalts formations, and it requires about 20 kg_{H2O}/kg_{CO2} brackish water.

Use and discharge of water by a Norwegian operator will need relevant permits from authorities and may even require a water treatment plant.

Land use

As referred in the IEAGHG report, Climeworks estimates that 1 Gt_{CO2}/y DAC facility would use 64 km^2 for the base plant. DAC systems using waste heat and natural gas would take less space since the land allocation for the energy supply would drastically drop. Furthermore, DAC plants do not require any arable land, allowing it to be placed on lower quality land if it has access to infrastructure and energy sources. IEA report suggests different values considering 1 mill. t_{CO2}/y and excluding provision of input energy needs: 0.4 km^2 for the liquid-DAC and 1.2-1.7 km^2 for the solid-DAC [7]. The liquid-DAC requires less land to get the same capture capacity. However, IEA reports that emerging electro-swing adsorption DAC (ESA-DAC) has the potential to Further reduce the land footprint up to 0.02 km^2/mill. t_{CO2}. While this could be a clear advantage of the ESA-DAC, its current TRL is too low to be able to quantify its potential when deployed on large scale. This is true even considering that ESA-DAC is a fully electricity-driven process, thus, the land footprint for the energy farm could be more relevant than for the other cited solid- and liquid-DAC.

Finally, the NASEM report points out the issues related to the air contactor volume and soil occupation and CO_2 capture land intensity. In addition to this, the air contactor structure could not be installed in several consecutive arrays close to the others. Indirect land use accounts for the spacing between contactors rows to match the DAC capacity. Indeed, if there was not enough distance between the arrays, there is no room for air mixing, thus, the inner contactors would process air with a lower CO_2 concentration than nominal (< 400 ppm). This would worsen the contactor performance leading to a waste of volume and capacity. Thus, there exists a minimum distance between the arrays of air contactors to guarantee equal inlet air conditions to each air contactor. NASEM provides some estimates for the 1 mill. t_{CO2}/y facility with a capture rate (yield of the process) ranging 65-75%.

In the air contactors designed by Keith and Holmes, the cross-sectional area is normal to the land surface. This use of the vertical space minimizes the direct land coverage since the equipment develops on the vertical direction. A structure containing packing of the dimensions of 20 m height by 200 m long and 8 m wide guarantees an inlet area of 4000 m^2 for the polluted air. If the packing bed is housed in a shell structure that is 110% of the packing dimensions, then the land use is roughly 2000 m^2 per contactor (which is half the exposed cross-area). This means that the air contactor is minimises the land allocation. From the calculations done in the report, around 19 000 m^2 is the surface occupied by the air contactor. A centralized regeneration facility including the causticizer, slaker, calciner, ASU, and other ancillaries is expected to have a direct land impact of 20% that of air contactor array. The surface allocation for the DAC facility is close to 24 000 m^2. When indirect land use is considered, the total land (regardless the single or multiple layers plant) the land requirement jumps by about 300 times the base case (thus around 7 km^2). Similar contactor spacing constraints exist also for solid-DAC. DAC company estimates that a single DAC facility has a specific capacity of 200-1370 kg_{CO2}/m^2 and the only DAC plant occupies 0.8-5 km^2 for 1 mill. t_{CO2}/y. The land requirement increases to 2.2-3.3 km^2 (accounting for natural gas-based thermal and electrical energy supply) or 5.5-9.9 km^2 (gas-based thermal energy and solar-based electrical energy). The proposed numbers once again emphasize the impact of the onsite power island/station.

Energy carbon footprint effect and global DAC footprint

The quality and the source of the electrical energy and heat matter. Indeed, the carbon footprint of the external inputs affects the global CO_2 capture efficiency of the DAC facilities. The net CO_2 capture efficiency grows as long as the low-carbon intensive energy sources are adopted. This is a natural consequence. The DAC is a negative emission technology NET, and this means that more CO_2 is capture than released to the atmosphere. If the electricity and the heat energy come from high-carbon intensity sources (such as coal and fossil fuels) the net-negative effect would be lower because more CO_2 would be released to the atmosphere to capture the CO_2 in the air. Conversely, low-carbon intensive sources such as renewables fits with the concept of DAC [6,7,9,61,100,100].

As an example, using solar energy for both thermal and electrical energy would result in a green house gas footprint of 8.4-18 000 t_{CO2}/y, while coal source 470-740 000 t_{CO2}/y. Deutz and Bardow show the CO_2 capture efficiency as a function of the carbon intensity of the electricity for different EU nations grids for solid-DAC. Their result demonstrates that DAC is a NET, but quality of the heat and process configurations may jeopardise the environmental positive effect. The same conclusion can be drawn for liquid-based DAC. In the Carbon Engineering plant, currently, the thermal energy is supplied through fossil fuel combustion, however, to lower the carbon footprint, electrolysers may in the future be installed to produce the hydrogen to provide the high temperature heat for calcination. Similarly, Terlouw et al. [100] performed LCA for different solid-DAC configurations considering different electricity and thermal energy sources using database data for the carbon intensity of the national grid, for instance. They draw interesting conclusions: (1) renewables are the perfect energy suppliers for DAC facilities, (2) the waste heat can be perfectly integrated to DAC systems, and it benefits to the global CO_2 sequestration efficiency, (3) the possibility to build the DAC facility close to storage sites reduce the impact of the transport, and (4) fossil fuel-based grid electricity should be avoided. For the latter point, the NASEM estimated that using coal as thermal and electrical energy source results in nearly equivalent emissions of CO_2 as than captured. Further, Terlouw et al. emphasize that the availability of large renewable excess (or in general low-carbon intensive grid electricity), waste heat sources (such as geothermal), but also the location close to storage sites may be limiting. The land requirement for renewables is not negligible and this is another element which limit the deployment of fully low-carbon electricity-driven DAC plant. Nevertheless, they accounted for a wide range of options for the energy supply in the LCA. The results demonstrate that energy-supply and electricity-used are the key factors driving GHG emissions of DAC deployment. The carbon removal efficiency is country-dependent, however, in most of the cases the “net-negative” is preserved (from 9 to 97% carbon capture efficiency).

Waste

Waste from a DAC plant should be handled according to permits given. Some of the waste will be of a typical composition for any chemical industry, e.g. used lubrication oil, food waste from canteens.

Special types of waste would be used adsorbent that has lost its capacity for CO_2 adsorption. In some cases the lifetime could be a few years, generating substantial amounts of waste. Adsorbents can possibly be treated in some way to be reused. As the chemical constituents are not know for many of the suggested adsorbents, guidelines cannot be given at this time. The handling of sorbent waste will depend on the type of sorbent. Some may be inert material that can be landfilled, while other may have to be processed before final disposal. Incineration can also be an alternative for some types of adsorbents. Waste handling should be an integral part of permits.

Emissions

There is no information on any chemicals that may be emitted from these processes. Some of the suggested adsorbents contains chemical substances to enhance the binding of CO_2. Given the huge volumes of air drawn through the contactors there is a as possibility that some chemicals may enter the outlet air stream. This needs to be addressed by authorities during the permitting process. Even though the concentration of such chemicals would be very low, given the large air volume, it may be harmful, e.g. for vegetation exposed for a log period close to a DAC plant.

Technology deployment: which is the best location?

General overview of potential best locations

Recently, Sendi et al. investigated the impact of the environmental conditions (temperature and air humidity) on the DAC energy consumptions and the specific cost of the captured carbon dioxide. Understanding the interplay between DAC plant performance and different climate conditions can help identifying regions with high potential for DAC plants deployment. Indeed, not all locations are equal, and some areas are better than others. Earth is divided into four regions (Figure 26) according to average temperature and humidity during the year. In their model, the author limited to solid-DAC systems. Meteorological statistics states that Norway fits cold humid cluster (average temperature ranging between -15°C [68] and 18°C and mean relative humidity [RH] > 65%). This is further confirmed and outlined in **Error! Reference source not found.** which depicts the temperature oscillations and the daily average temperature across the year in two Norwegian locations (Fedje and Mosjøen).

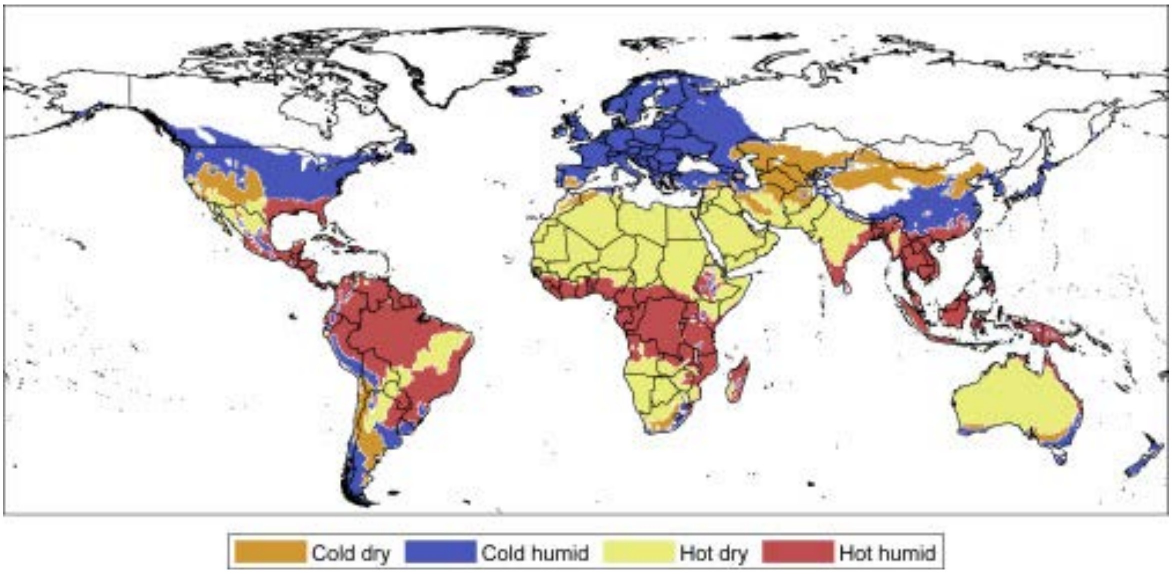

Figure 26 – Climate aggregation based on yearly average temperature and relative humidity above and below 18°C and 65%, respectively. Regions where the temperature drops below −15°C more than 30 days per year are excluded (picture reproduced from Sendi et al., Geospatial analysis of regional climate impacts to accelerate cost-efficient direct air capture deployment, One Earth, Volume 5, Issue 10, 1153 – 1164 under Creative Commons Attribution License CC BY 4.0)

In general, depending on the ambient temperature, the collector productivity increases while the electricity demand drops at mild relative humidity (20-60%). This is mainly caused by the enhanced adsorption of the CO_2 on the amine-functionalized adsorbent assisted by the water itself. The positive effect vanishes at higher RH as the sorbent water loading increases leading to an increment of the heat consumptions to regenerate the material. Looking at the distribution of the capacity and energy requirement, the productivity is higher in low-RH and low-temperature. However, the productivity sharply decreases below 41 t_{CO2}/y per collector where the temperature drops below -15°C. These regions have been neglected since the adsorbent material have not been tested and designed to operate in such environmental conditions. Moreover, the authors realised that the capture costs could sharply burst to unfeasible level (> 750 USD/t_{CO2}). Further, the authors notice that low electricity requirement regions can be found in drier regions with lower HR. The highest DAC plant productivity (Figure 27A) has been found in cold dry regions where the capacity can reach up to 55.1 t_{CO2}/y per collector with an average of 51.6 t_{CO2}/y. This DAC facilities should consume on average 1.76 MWh_{el}/t_{CO2} of low-carbon electricity. After that, cold humid regions have better productivities (49.8 t_{CO2}/y) compared with hot dry regions (48.6 t_{CO2}/y). Despite the lower productivity per collector, hot dry regions have the lowest specific energy consumptions (1.64 MWh_{el}/t_{CO2}) against the cold humid regions (2.15 MWh_{el}/t_{CO2}). Finally, the hot and humid regions present

[68] Lower limit represents the minimum tested temperature for most of the adsorbent material (Climeworks Lewatit)

the worst performance with low productivity (46.9 t_{CO2}/y) associated with relatively high specific energy input (2.11 MWh_{el}/t_{CO2}).

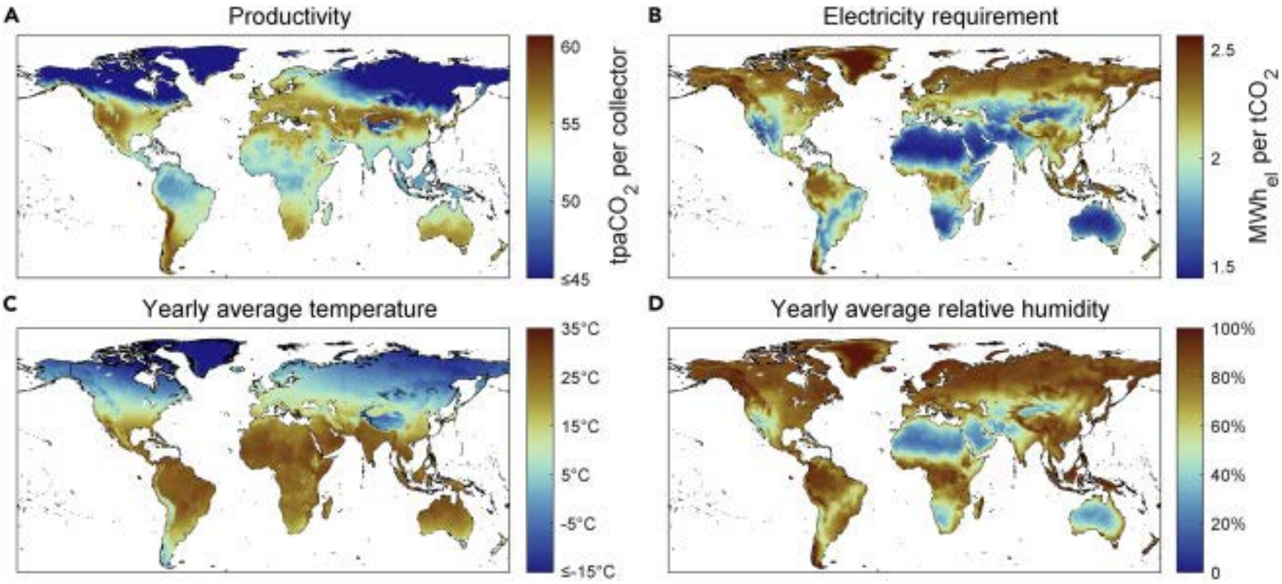

Figure 27 – DAC global performance (A) CO_2 collector productivity obtained using hourly CO_2 production averaged over the year, assuming −15°C as a minimum operating temperature for the DAC plant. (B) The average electricity requirement for the yearly CO_2 production. The current benchmark DAC solid-sorbent (i.e., Climeworks Lewatit VP OC 1065) is used when calculating global productivity (A) and electricity requirement (B) where future climate-tailored sorbents can be developed, potentially impacting regional differences in DAC performance. Also, it is assumed that when the temperature is below 1°C, process performance is fixed to the performance of operating at 1°C. (C) Yearly average temperature. (D) Yearly average humidity (picture reproduced from Sendi et al., Geospatial analysis of regional climate impacts to accelerate cost-efficient direct air capture deployment, One Earth, Volume 5, Issue 10, 1153 – 1164 under Creative Commons Attribution License CC BY 4.0)

DAC deployment in Norway: some considerations

The results show that Norway has potential for solid-DAC deployment both in terms of capacity and capture costs since it has a cold humid clime (Figure 26). Figure 27 outlines that the Climeworks module can reach middle-high capture capacity around 50 t_{CO2}/y, but the electricity consumption is still high and close to the maximum. Despite the energy consumption drawback, Figure 28 depicts that the capture is still relatively “cheap” (< 550 USD/t_{CO2}) even considering the worst scenario (high electricity cost) and compared to several other areas. Currently (2022), the average electricity cost in Norway is close to the second scenario proposed in Figure 28 (50 USD/MWh), though there are large regional differences. Variations in prices is partly due to current situation in Europe and the increased proportion of intermittent production by wind and solar. Under this assumption, solid-DAC LCOD are expected to range (375-425 USD/t_{CO2}) and Norway is one of the cheapest country where deploying DAC facilities. It is noteworthy that the proposed results are just related to simulations, and not validated on the industrial scale yet. This means that the comments and results are just speculations even though these can provide a good insight on the potential of the DAC solution in Norway. In addition to this, the analysis probably does not account for potential issues when DAC is located in cold climate and close to the sea/ocean as in Norway. Frosting and potential corrosion problems are local/national aspects, thus, specific country-by-country.

As far as we know, there are no studies that specifically investigated the best location and the specific costs of either solid- or liquid-DAC for Norway or Scandinavian area. The conclusion is that there are so many (specific) factors that can come into play that it is not possible to give any clear recommendation now on which is the best location in Norway. The technology suppliers must test the technology and choose a solution or technical improvements to overcome issues specific for Norway which are not included in the current literature and studies.

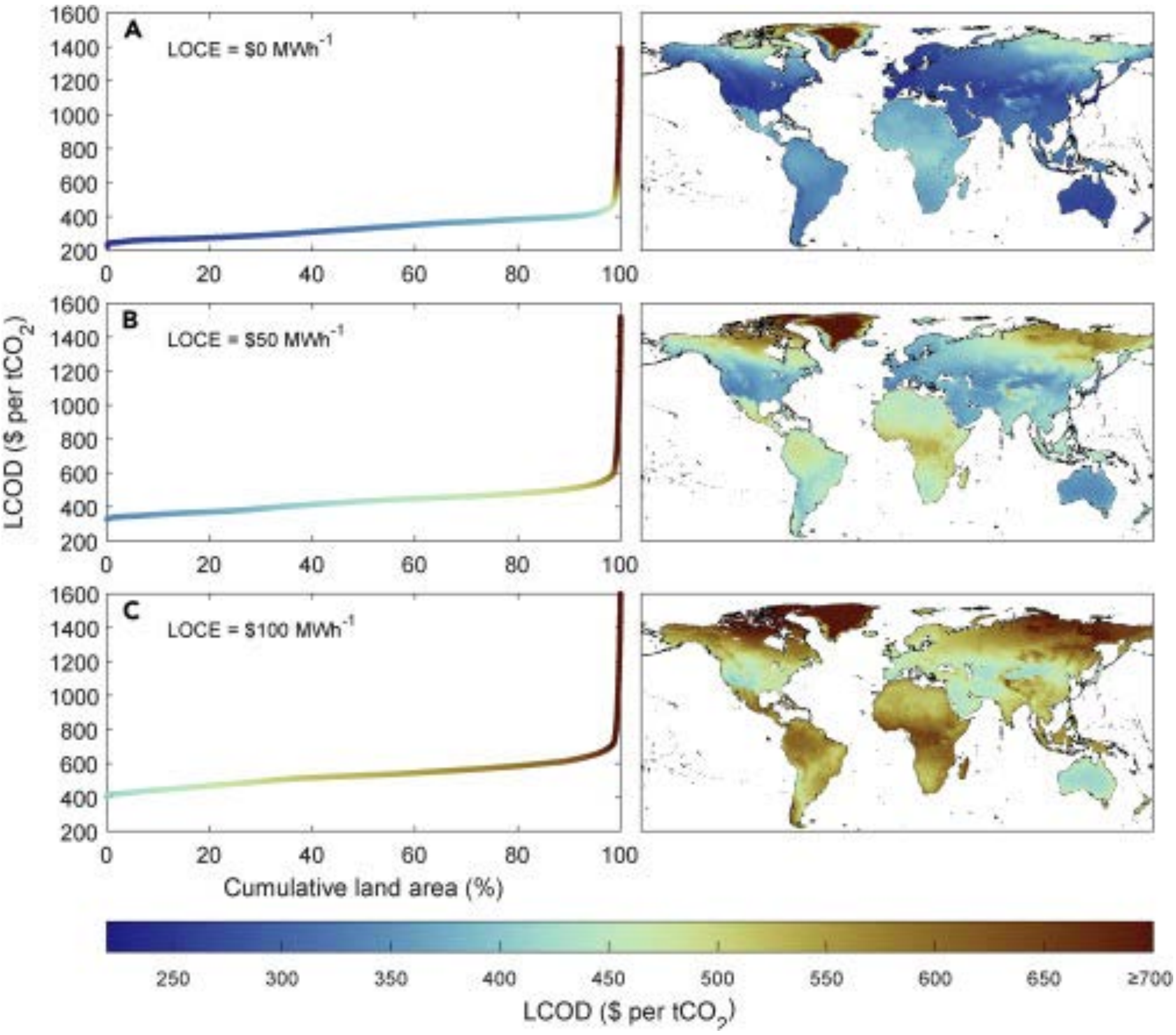

Figure 28 – Global cost and supply curve for vacuum temperature swing adsorption (VTSA). The left figures show the global DAC supply curves at different LCOEs as a function of total land that can deliver DAC at the corresponding levelized cost of DAC (LCOD). The colour of the data points of the supply curves matches their location on the corresponding map on the right. Darker blue indicates a cheaper LCOD, and darker brown indicates a more expensive LCOD (picture reproduced from Sendi et al., Geospatial analysis of regional climate impacts to accelerate cost-efficient direct air capture deployment, One Earth, Volume 5, Issue 10, 1153 – 1164 under Creative Commons Attribution License CC BY 4.0)

The farther north in Norway the greater the possibility for ice formation on and in contactors. Most likely a DAC plant will have to shut down in adverse weather conditions. For instance, Lewatit and other adsorbents have not been tested below -15°C. The performance of solid-DAC are uncertain close to these cold conditions as also remarked in Sendi et al. [51]. In the same work, the implemented model shows that even if the solid-DAC could work the costs increase. For this reason, in Northern Norway the down time may significantly increase the cost of DAC per ton of CO_2 captured. As there may be difference in the DAC technologies as to their sensitivity to temperature and humidity certain technologies may better suited in northern parts. Seaspray and aerosols may necessitate anti-corrosion measures that must be taken into consideration during engineering and maintenance and will normally increase costs. One should also take into consideration air quality, as pollutants like NOx and SOx may contaminate sorbents. Looking at the Norwegian context (also considering industrial clusters which could share facilities), two locations have been suggested as locations for DAC plants: the CCB Energy Park in Øygarden municipality west of Bergen and Mosjøen in Vefsn municipality in Nordland County. These two locations are selected for the two hypothetically plants discussed in section 7.

Technology Readiness Level (TRL)

The Technology Readiness Level (TRL) is a key aspect when dealing with new technologies since it snapshots the status of a technology and the missing steps to a full industrial scale deployment. Figure 29 outlines the several steps and readiness levels (from TRL-1, conceptual idea, to TRL-11, proof of stability) to be accomplished before a novel technology can be considered conventional or at least fully developed and available for the market. Figure 29 outlines a novel TRL scale that IEA adopts to assess novel technology. It is based on the EU Horizon scale with further distinctions on the high TRL. Arriving at a stage where a technology can be considered commercially available (TRL 9) is not sufficient to describe its readiness to meet energy policy objectives, for which scale is often crucial. Beyond the TRL 9 stage, technologies need to be further developed to be integrated within existing systems or otherwise evolve to be able to reach scale; other supporting technologies may need to be developed, or supply chains set up, which in turn might require further development of the technology itself. For this reason, the IEA has extended the TRL scale it uses in its reports to incorporate two additional readiness levels, which focus on market (rather than technology) development: one where the technology is commercial and competitive but needs further innovation for its integration into energy systems and value chains when deployed at scale (TRL 10), and a final one where the technology has achieved predictable growth (TRL 11). In addition, the TRL jump is a very time demanding process, and it takes several years. It has been calculated on average at least ten years for the chemical industry from the lab-scale proof-of-concept to TRL-9 [101,102]. The main concern is the time demand for the last jump from TRL-9 to TRL-11 according the new TRL-scale proposed by IEA. Moreover, the financial resources needed for an industrial validation (TRL > 6) and the associated costs “exponentially” growth with the risks. Large capital investments require appropriate investors and risk-management tools [101,102]. Finally, the last steps (TRL 10-11) involve also socio-economic aspects which may complicate the technology deployment. For instance, legislation and policies should support the DAC to fill the gap into the current capture costs with other NETs such as BECCS and biochar [69,100,103]. Nevertheless, also the society acceptance and perception of a novel technology influence the deployment [104].

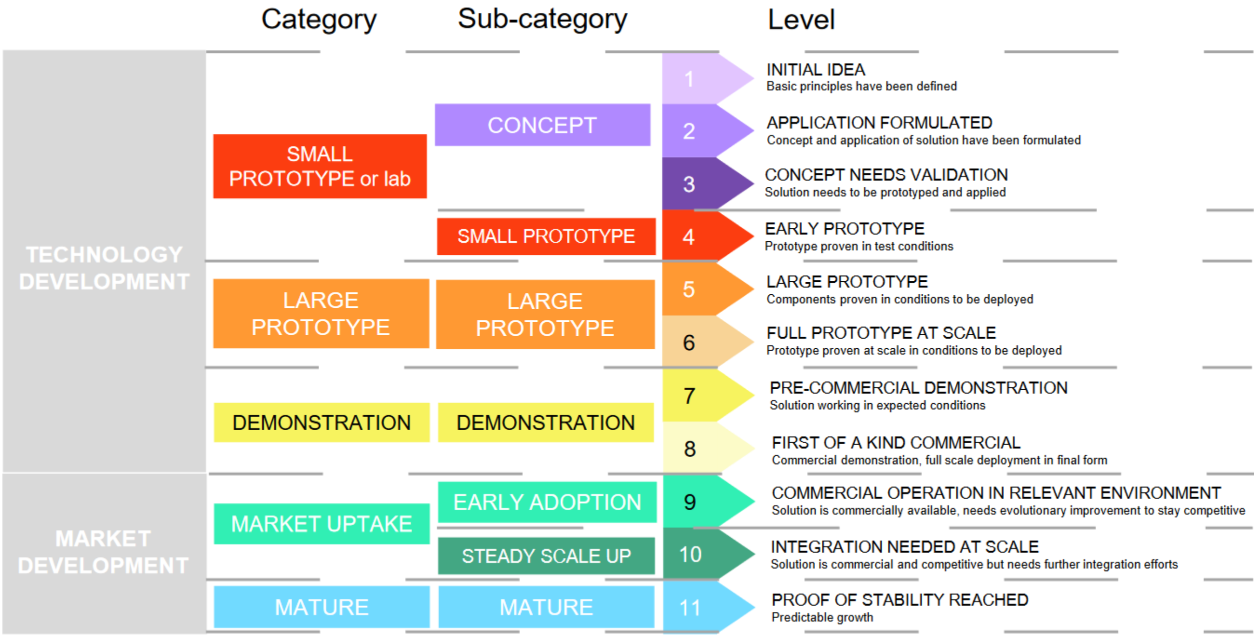

Figure 29 – Maturity categories and TRLs along innovation cycles according to IEA (picture reproduced with permission from the International Energy Agency, Direct Air Capture – A key technology for net zero, IEA report, 2022, all rights reserved)

For the DAC technologies it is quite complex and difficult to determine the TRL for the different technologies once again due to lack of updated information of the planned activities by the DAC companies. TRL has tight entanglement with TEAs. Indeed, TRL is not so high as to accurately make any predictions or calculations for future of the DAC performance (largely because DAC technology is at its infancy) [82,105]. Leonzio et al. [13] and Chauvy and Dubois [81] tried to classify the technologies according to TRL, but they fail in providing a narrow and sharp window or range. In the light of planned plants (Table 7) and updates research activities (Table 6), we tried to provide a more tight and precise indication of the current TRL for the different technologies (Figure 30) using the IEA criteria (Figure 29) for the listed DAC companies in paragraph 3-Technologies including DAC business .

- Climeworks has the highest TRL (8-9) since the they are operating more than ten pilot plants and they have planned large-scale plants for the next 5 years. It is remarkable that for adsorbent-base DAC the plant size and target are small than for liquid-based DAC [5,7,53,69]. The target size for a full scale solid-DAC is around 0.1 – 1 mill. $_{CO_2}$/y, while for liquid-DAC larger than 1 mill. $_{CO_2}$/y. Climeworks has already built a FOAK DAC and operated a plant in a relevant environment. Thus, its technology TRL is at least 8-9, but not higher since the solution is not still commercial and competitive (TRL-10) and the proof of stability (TRL-11) is not validated yet.
- Carbon Engineering is building its FOAK plant of industrial relevance and the TRL is 7-8. Conversely, TRL-9 is not suitable for this solution yet since the demonstration of the technology in a relevant environment is only planned.
- Global Thermostat is the most difficult company to be classified since information is missing. Table 7 reports that 100 – 230 000 t_{CO_2}/y are planned for 2023. However, it is not clear the status of the TRL jump. As far as we know, the maximum DAC size is below 100 000 t_{CO_2}/y until 2021. In addition, Global Thermostat has not advertised any intermediate achievement such as small-scale pilot plant (up to 1-5000 t_{CO_2}/y) successfully operated[69]. For this reason, at the current state, we

[69] Climeworks advertised the operation of small-scale plants in Hellisheidi (Iceland) and Hinwil (Switzerland) [61,72]

assume that Global Thermostat technology TRL is lower (than Climework), and they are approaching the so-called demonstration phase.

- Verdox technology has been validated on the lab scale [21,106] and probably in small prototype [106]. They started the scale-up for small scale prototype to figure out some features of the technologies from simulations [23]. Thus, the TRL is expected ranging 3-4.
- CSIRO validated the CO_2 capture using amino acid salts solutions, while recently Rolls-Royce financed a small pilot plant (100 t_{CO2}/y) demonstration [29,30]. Thus, they are going to proof the technology on small prototype for liquid-DAC (TRL-4). As CSIRO, Mission Zero Technology (MZT) has a small pilot plot (120 t_{CO2}/y) planned for 2023.
- GreenCap validate the solid-DAC technology for small-scale plant (300 t_{CO2}/y). This technology is available already for greenhouse culture which is a niche market. We could expect that GreenCap could be interested to deploy its technology also for CO_2 sequestration purpose (basically as Climeworks and Global Thermostat). Thus, the prototype is fully validated for the market of greenhouse agriculture (TRL 7-8).
- Kawasaki tested its own adsorbent material on small-scale prototype (44 t_{CO2}/y) thus the technology is TRL-4 and they are planning to increase the adsorption column size to validate the technology and adsorbent stability over a semi-industrial scale (i.e., jump to an intermediate TRL 4-5).
- BPMED has been validated on lab-scale and probably on a small-prototype (TRL 3-4). The main concerns are the cost of the membrane for the electrodialysis and the electrical energy consumption. What could stop the development of the technology in absence of any improvements in these directions, despite it represents a full electrification of the Carbon Engineering process.
- Susteon Inc. is investigating a module where both DAC and methanation are performed in series. Currently, the adsorbent material has been fully defined and investigated, thus, next steps will focus on the engineering of the prototype and the validation of small-scale systems (TRL 4).

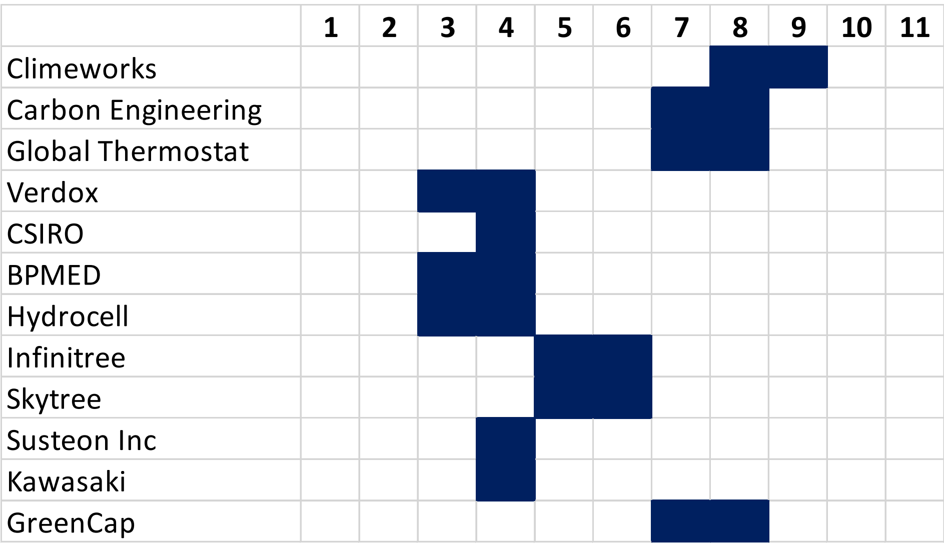

Figure 30 – DAC technologies TRL estimate based on Table 6 (history of recent research activities) and Table 7 (planned plants)

Social acceptance of DAC

Like any technology, public perception and acceptance may be a critical factor for a large-scale DAC deployment or inclusion in decarbonisation strategies adopted all around the world.

Only a few articles in the literature deal with the public acceptance of DAC, but a couple of surveys indicate how the general public in UK and US perceives DAC in comparison to other negative emissions technologies (NETs). For instance, a large English public engagement survey to investigate the public attitude to combat climate change shows that the respondents have more trust in afforestation and any action to re-establish ecosystems balance [107]. The support to both BECCS and DAC were preferred by 42% of the respondents. The results are mainly due to perception that these solutions are less natural and may distract the attention on the real problem presented by emissions. Similarly, a survey done across US and UK reports similar results and feedbacks [104]. The participants had somewhat negative attitudes towards NETs because they perceived these technologies not to be a short-term solution and not form part of an ideal long-term climate portfolio since they imply continued emissions elsewhere in the economy.

7. Case studies for potential DAC plants in Norway

In this chapter, we look at two hypothetical cases for a DAC plant in Norway. The hypothetical cases are loosely based on possible plants that are considered in Norway, using existing technical solutions. However, all calculations are our own based, on existing literature and similar technologies (presented in the chapters above). We also look at different technical adaptations to the two cases based on the source of energy used in different parts of the plants.

Two hypothetical cases

Below we describe the two hypothetical cases.

Case A – liquid process

The hypothetical case A is based on the TEA of Keith et al. [8] and modified according to the standard factor estimation techniques used by SINTEF. The plant is using a Carbon Engineering like process, where CO_2 is first captured in an alkaline solution (KOH or NaOH) and then converted to solid calcium carbonate. The carbonate is treated at a high temperature (higher than 850°C) to release nearly pure CO_2 gas which can then be liquified and purified before storage (or use). A turbine is used to produce electricity and steam. An oxyfuel burner (on natural gas) is used for the high temperature calciner. CO_2 from the use of natural gas is captured together with CO_2 from the air.

The technology is the same as Carbon Removal intends to use, and therefore we imagine the hypothetical plant to be located where they are planning to install the plant: in or close to CCB Energy Park in Øygarden. Benefits of this location is the access to natural gas, as the Kollsnes natural gas processing plant and the Gasnor LNG plant are in the vicinity, as well as the possibility of direct transport with pipelines from the plant to Northern Lights storage facilities.

In **case A.1** natural gas is used both for production of electricity (using a gas turbine) and for heating the calciner.

Another possibility is to use electricity from the grid. In **case A.2**, the gas turbine is not needed, but natural gas is still necessary to obtain the high temperature heat for the calciner. Electricity is assumed to be supplied through the grid. This is our **base case** for the liquid process technology.

In a longer perspective also the calciner can be electrified, which is our **case A.3**.

It is further assumed that the plant captures 1 mill. ton CO_2 (net). Together with the CO_2 from the burning of natural gas in case A.1, a total of 1.5 mill. ton CO_2 will need to be stored.

Case B – adsorption process

The hypothetical case B uses an adsorption process, where a bed of solid particles is used as the agent to bind CO_2. Adsorption is a discontinuous process: first CO_2 is adsorbed from air and a desorption step follows to release concentrated CO_2.

The case is based on Climeworks' technology, releasing CO_2 by temperature/vacuum swing process. At present, this technology is used at small scale and capturing 100 000 ton CO_2 per year seems reasonable to achieve. However, for comparison of the abatement costs, we scale the plant to the same capacity as case

A (capturing 1 mill ton CO_2 yearly). We comment on the implications of this assumption for the costs below.

This hypothetical plant is assumed to be located in Mosjøen (Vefsn minicipality) in Nordland county, which is the other of the two locations suggested for DAC plants in Norway.

In **case B.1** a heat pump is used to reach the necessary temperature, and waste heat is used free of cost.

In **case B.2** electricity from the grid is used to obtain the necessary temperature directly and there is no use of waste heat.

To summarize, we analyse the costs of the following cases:

A. A plant using a liquid process (Carbon Engineering-like technology), with a net capture of 1 mill. ton CO_2 per year. When studying this case, we look at three different alternatives:
    1 gas used both for the turbine and the calciner
    2 electricity from the grid used for the turbine, and gas for the calciner
    3 electricity from the grid used both for the turbine and the calciner
B. A plant using an adsorption process (Climeworks-like technology), with a gross capture of 1 mill. ton CO_2 per year, but with the possibility to downscale to a smaller scale at 100 000 ton/year. When studying this case we look at two different alternatives:
    1 heat pump is used to reach the necessary temperature for desorption of CO_2
    2 electricity is used for the necessary temperature for desorption of CO_2

In our analysis, case A.2 and B.1 are our base cases for the technologies. In the following sections, we discuss some key aspects to consider before establishing a DAC plant in Norway, based on these two hypothetical cases.

Area for a DAC facility

As described, a significant area is needed for a DAC plant. Figure 31 shows approximately the planned location of Carbon Removals plant in Øygarden. The plant is scaled to capture 500 000 ton CO_2 per year, and the area indicated for the plant is 135 000 m^2 (equal to 13,5 ha or approximately 20 football pitches). Roughly, the area is doubled for a plant capturing 1 mill. ton CO_2 per year as in case A. Extra area may be needed during construction for intermediate storage, etc. This is in line with other estimates of area used [6,7,9,51].

An aerial photograph of CCB Energy Park with the construction site for Northern Lights CO_2 hub on the right (northern part of the Energy Park) is shown in Figure 32. The photo is taken the summer of 2022 from the east. A possible location for the DAC plant is behind the Gasnor LNG tank on the left end of the photo.

A DAC plant using the adsorption process capturing 100 000 ton CO_2 per year is assumed to occupy around 150 000 m^2 of land area.

Figure 31 – Map showing the possible location of a DAC plant in Øygarden (modified from Norgeskart.no)

Figure 32 – Panorama of CCB Energy Park (Photo courtesy of CCB Energy Park holding)

Climatic conditions

It is likely that a DAC plant will have to shut down in adverse weather conditions, Sendi et al. [51], and the farther north in Norway, the greater the possibility for adverse weather conditions. Low temperatures may result in ice formation on and in contactors. In Northern Norway, the down-time may significantly increase the cost of DAC per ton of CO_2 captured. In addition to the reduction in operating time itself, isolation and securing the plant during downtime may add to the operating and capital costs.

As there may be difference in the DAC technologies as to their sensitivity to temperature and humidity, some technologies may be better suited in northern parts. However, there is not enough information available as of now to give any recommendations.

To illustrate how temperature changes with location, we study last years' temperatures measured for the two alternative locations in our cases. For the plant located in Øygarden in case A, we use the temperature measured at Fedje meteorological station, 25 kilometres north of the Northern Lights CO_2 hub in the Energy Park. For the plant located in Mosjøen in case B, approximately 600 kilometers further north, we use the temperature measured at Mosjøen airport. The temperatures are presented in Figure 33.

While Fedje and Øygarden has very few days with sub-zero temperatures, Mosjøen has almost six months with ai which the majority of days have sub-zero average temperatures. Hence, the cost of direct air capture may be significantly higher in Mosjøen than Øygarden, due to adverse weather conditions and and long periods of down time. Only testing DAC technology in different weather conditions can inform about what is considered acceptable weather conditions.

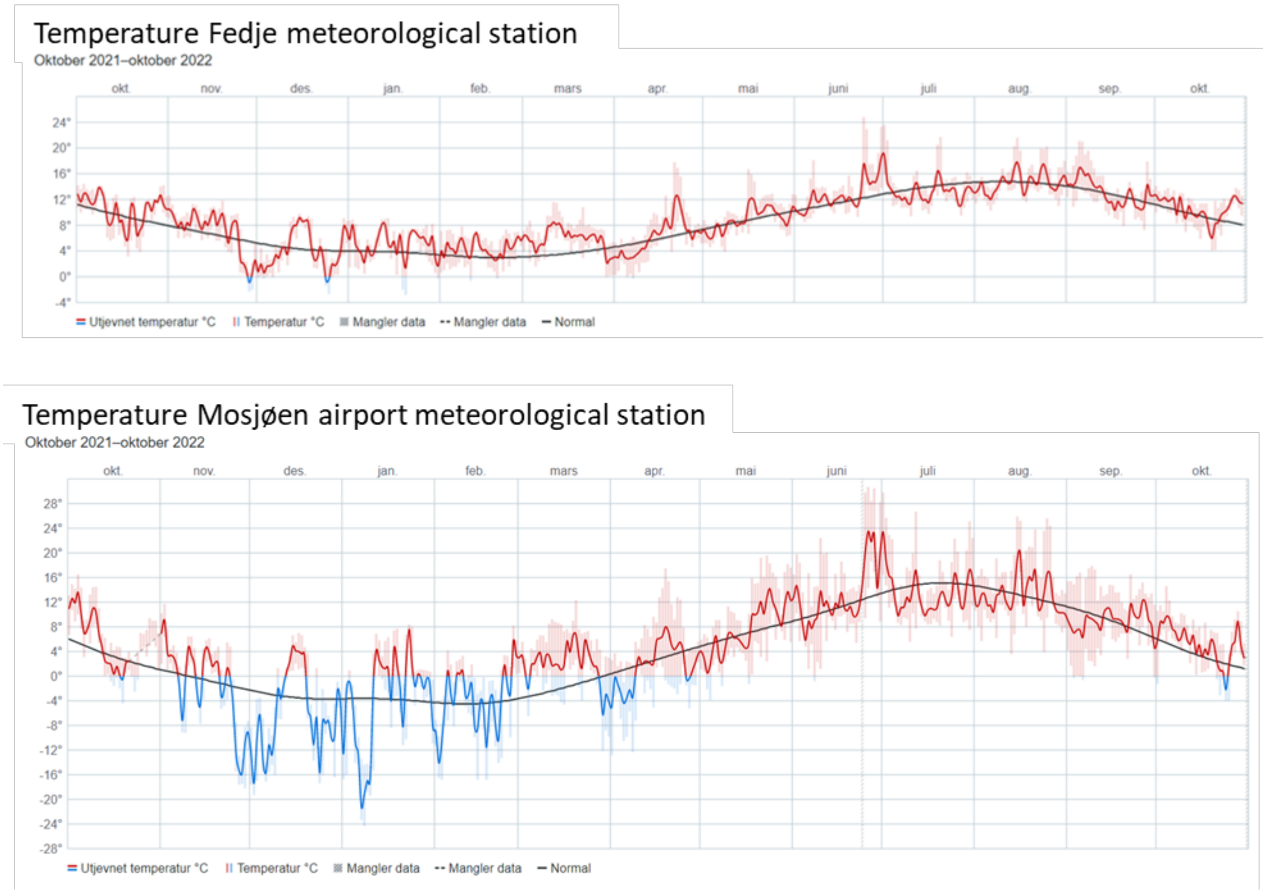

Figure 33 – Temperature graphs for Fedje and Mosjøen

Another factor to consider when locating a DAC plant is that sea-side locations will be subjected to sea spray and aerosols containing chlorides that may accumulate in the sorbent and may also be corrosive to external surfaces in the plant. Anti-corrosion measures must be taken into consideration during engineering and maintenance and will normally increase costs. On the other side, a seaside location may also be beneficial as there is a better circulation of air. Furthermore, locations along the coast with direct access by ship will reduce transportation costs as transport by lorry is avoided. Lorry transport of liquid CO_2 is planned for several of the CCS projects on flue gas from existing industrial processes.

Lastly, one should also take into consideration air quality, as pollutants like NO_x and SO_x may contaminate sorbents.

Investments and operational costs

Table 11 summarizes the operational and investments costs of the different technologies in our cases.

Costs in case A.1 (liquid process) are estimated *bottom-up*, using existing literature and standard factor estimation techniques. Case A.2 and case A.3 are versions of case A.1, based on the same estimations but with different energy sources. We assume an electricity price of 53 USD/MWh, based on NVE (2021).[70]

Costs in case B (adsorption process) are estimated *top-down*, from an assumed capture cost of 600 USD per ton CO_2 for a 100 000 ton/year plant and a CAPEX percentage of 33 based on IEAGHG.[71] In these cases, an electricity price of 42 USD/MWh is assumed, based on NVE (2021).

In both cases it is assumed a gas price of 50 USD/MWh (15 USD/MMBtu). The difference in electricity prices is explained by the hypothetical plants being located in different price regions, see NVE (2021).

Technology	Annual		Investment
	OPEX	CAPEX	
A.1 Liquid based process (Carbon Engineering-like), fully powered by gas	197	86	1 119
A.2 Liquid based process (Carbon Engineering-like), electricity from grid, gas fueled calciner	184	86	1 119
A.3 Liquid based process (Carbon Engineering-like), electricity from grid, including electrically heated calciner	204	86	1 119
B.1 Adsorbent based process (Climeworks-like) with heat pump	389	122	1 589
B.2 Adsorbent based process (Climeworks-like) without heat pump	395	122	1 589

Table 11 – Investment cost, operational cost, and capital expenses, million USD

Cost components

Figure 34 shows the allocation of costs on capital expenses, energy costs and other operational costs for the hypothetical plants. With the liquid-based process in case A, each of the three make up approximately one third of the costs (37-35-28 percent). With the adsorption-based process in case B, energy makes up a much smaller share of total cost, less than 20 percent, while other operational costs make up 35 percent and capital expenses almost 50 percent.

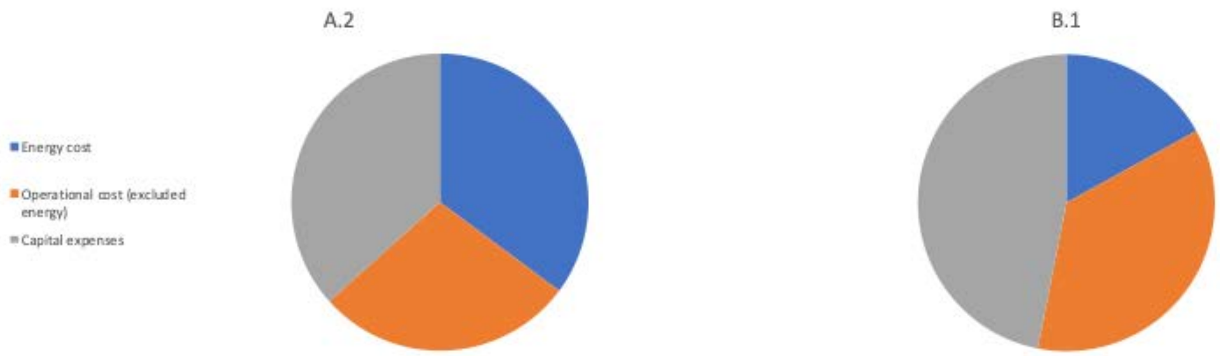

Figure 34 – Shares of energy costs, other operational costs and capital costs in hypothetical cases A.2 and B.1

[70] NVE (2021): «Langsiktig kraftmarkedsanalyse 2021 – 2040», NVE rapport nr. 29/2021. Available at rapport2021_29.pdf (nve.no)
[71] Costs are scaled from a 100 000 ton CO_2 plant to a 1 mill. ton CO_2 plant, to be comparable to case A.

Figure 35 present capital costs, energy costs and other operational costs allocated to each cost component with the liquid-based process in case A. The three major cost components are the calciner slaker, the air contactor and the pellet reactor which together make up for almost two thirds of the total costs. Energy to the calciner make up around two thirds of the costs related to the calciner and is the single greatest cost component with this process.

Disaggregated costs for case A.1 and B.1 are further presented in appendix A.3.

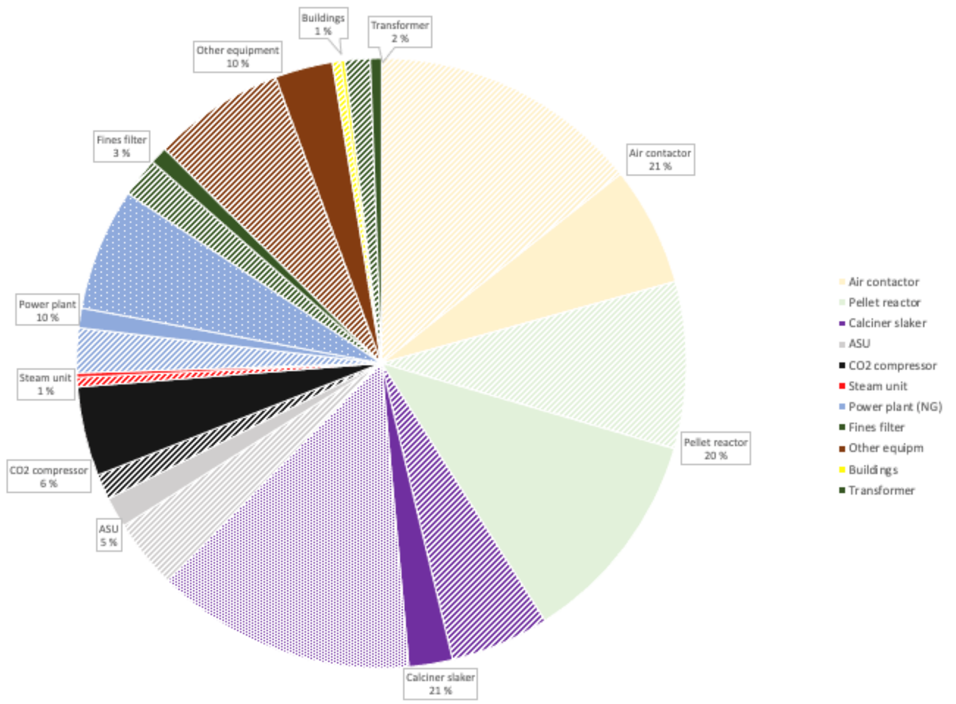

Figure 35 - Cost components for case A. Operational costs in solid fields, capital expenses in dashed fields and energy costs in dotted fields.

Abatement cost – base case

In order to compare the hypothetical DAC plants with other abatement possibilities, we need to calculate the abatement cost accordingly to the method used in Klimakur 2030.[72] These methods are described in the Norwegian Ministry of Climate and the Environment's guidelines.[73] The guidelines distinguish between **socio-economic abatement costs** ("*samfunnsøkonomisk tiltakskostnad*"), and **private abatement costs** (*"bedriftsøkonomisk tiltakskostnad"*).

Socio-economic abatement costs are calculated by dividing the net present value of total costs by the total amount of CO_2 captured over the economic lifetime of the investment. We assume an economic lifetime of the investment to be 25 years, based on typical chemical process plants with 2 years building phase and 23 years of operation.

[72] Klimakur 2030: "Klimakur 2030: Tiltak og virkemidler mot 2030». M-1625. Miljødirektoratet, Enova, Statens Vegvesen, Kystverket, Landbruksdirektoratet, NVE. https://www.miljodirektoratet.no/klimakur
[73] Miljødirektoratet (2019): Metodikk for tiltaksanalyser. Veileder. Miljødirektoratet M-1084. https://www.miljodirektoratet.no/globalassets/publikasjoner/m1084/m1084.pdf

A yearly rate of 4 percent is used to discount the future costs, in accordance with the Ministry of Finance guidelines for economic analysis.[74] Future CO_2 volumes are not discounted, i.e., one ton of CO_2 captured in 2040 is valued equal to one ton of CO_2 captured today.

We do not include other costs, such as costs of the area, infrastructure, transport or storage of the captured CO_2, noise, other damages to nature, wildlife, etc.

To calculate the **private abatement costs**, we:

- include relevant taxes and fees
  - we add 21 percent to the electricity price to include transmission tariff and taxes,
  - we add 25 percent to the gas price and capital expenses, and 10 percent to the operational expenses, to include taxes and fees.
- adjust the discount rate to 8 percent to reflect the expected rate of return in the market, and
- discount future CO_2 volumes by the same discount rate.

As we have not identified external cost or benefits to the projects for the calculations of the socio-economic abatement costs, these adjustments are the only differences between the private and socio-economic abatement costs.

Furthermore, we use the assumptions shown in Table 12 (based on the literature discussed above):

Technology	Gas use (MWh)	Electricity use (MWh)	Energy cost (M USD)	OPEX excl. energy costs (M USD)	CAPEX (M USD)	Investment (M USD)
A.1 Liquid based process (Carbon Engineering-like), fully powered by gas	2 396 833	-	130	77	86	1 119
A.2 Liquid based process (Carbon Engineering-like), electricity from grid, gas fueled calciner	1 630 333	488 808	106	77	86	1 119
A.3 Liquid based process (Carbon Engineering-like), electricity from grid, including electrically heated calciner	-	2 396 833	120	77	86	1 119
B.1 Adsorbent based process (Climeworks-like) with heat pump	-	1 368 056	68	332	122	1 589
B.2 Adsorbent based process (Climeworks-like) without heat pump	-	608 796	30	370	122	1 589

Table 12 – Base case assumptions for annual energy consumption (MWh), operational costs, capital costs and total investment (2 years) in million USD

[74] Finansdepartementets rundskriv R-109.

The socio-economic and private abatement costs, based on these assumptions, are shown in Table 13.

Technology	Socio-economic abatement cost (USD/t CO_2)	Private abatement cost (USD/t CO_2)
A.1 Liquid based process (Carbon Engineering-like), fully powered by gas	223	395
A.2 Liquid based process (Carbon Engineering-like), electricity from grid, gas fueled calciner	216	383
A.3 Liquid based process (Carbon Engineering-like), electricity from grid, including electrically heated calciner	228	402
B.1 Adsorbent based process (Climeworks-like) with heat pump	385	671
B.2 Adsorbent based process (Climeworks-like) without heat pump	389	677

Table 13 - Abatement costs ("tiltakskostnad") in USD per ton of CO_2 captured

Table 13 reveals that the socio-economic abatement costs for the hypothetical plants range from 216 USD to 389 USD per ton of CO_2. The estimates indicate the possible abatement costs of future DAC plants in Norway. However, the assumptions are associated with a great amount of uncertainty; therefore, these estimates should be treated cautiously.

As mentioned, the Case B plant can be downscaled. The costs for a smaller plant will be higher. For instance, the abatement costs of a plant with a capacity of 100 000 ton CO_2 are 12 per cent higher than that of a plant with a capacity of 1 mill. ton CO_2 in the base case.

All cases presented above are based on first-of-a-kind plant (FOAK), hence, costs may decrease as the technologies become more mature. We will discuss this below.

Sensitivity analysis of abatement costs

We study how the estimated abatement costs depend on assumptions about electricity and gas prices, investment and operational costs. Changes in investment costs also affect capital expenses in operating years.

Electricity price

We use the assumptions from low and high electricity prices from NVE (2021), see Table 14.[75] The assumptions reflect the different prices in different locations in Norway.

Case	Baseline	Low	High
A - Liquid based process (Carbon Engineering-like)	53	41	66
B - Adsorbent based process (Climeworks-like)	42	32	51

Table 14 – Alternative assumptions for electricity prices, USD/MWh

Abatement costs for the hypothetical plants are quite robust to changes in electricity prices within the most probable price scenarios, as shown by results from the sensitivity analysis presented in Table 15.

[75] «Langsiktig kraftmarkedsanalyse 2021 – 2040», NVE rapport nr. 29/2021. Available at rapport2021_29.pdf (nve.no)

The electricity prices in the low and high scenario vary only by approximately 20 per cent from the baseline. However, even if we double the expected electricity price to 100 USD/MWh, abatement costs increase only by less than 10 per cent in case A.2 (to 230 USD/ton CO_2) and around 10 per cent (to 435 USD/ton CO_2) in case B.1. Costs for Case A.1 do not change when electricity price changes, since it is fully operated by gas.

Case	Baseline	Low	High
A.2 Liquid based process (Carbon Engineering-like), electricity from grid, gas fueled calciner	216	212	220
B.1 Adsorbent based process (Climeworks-like) with heat pump	385	377	392

Table 15 – Abatement costs for different electricity price scenarios, USD/ton CO_2

Gas price

To test the sensitivity to gas prices, we base our scenarios on Rystad (2022)[76] and NVE (2021)[74], but adjust these to create scenarios which provide useful information for a sensitivity analysis.[77] Our scenarios are the following:

Baseline	Low	High
50	20	70

Table 16 – Alternative assumptions for gas prices, USD/MWh

Results of the alternative gas price assumptions are presented in Table 17. Case A is more sensitive to changes in gas prices than electricity prices. In our analysis the gas price is considered more volatile than the electricity price, with a greater outcome space and prices ranging from 20 to 70 USD/MWh. Price changes of this size may change the abatement cost by 10-20 percent, everything else equal.

Case	Baseline	Low	High
A.1 Liquid based process (Carbon Engineering-like), fully powered by gas	223	179	253
A.2 Liquid based process (Carbon Engineering-like), electricity from grid, gas fueled calciner	216	185	236

Table 17 – Abatement costs for different gas price scenarios, USD/ton CO_2

Energy price changes

To account for correlation in electricity and gas prices, we test the sensitivity of abatement costs when both gas and electricity prices are lower/higher than the baseline assumptions. As A.2 is the only case where both gas and electricity is used, it is the only case presented in Table 18. When we let both gas prices and electricity prices follow the low/high price scenarios described in the previous sections, the effects on abatement costs in case A.2 (partly electric) is similar to the effects of gas price changes in case A.1 (fully gas driven) in a low price scenario. In a high price scenario, the effects are smaller, as electricity prices is assumed to be less volatile than gas prices.

Case	Baseline	Low	High

[76] Rystad technical report available at Report-Rebalancing-Europes-gas-supply.pdf (iogpeurope.org)
[77] We use a conversion rate of 3.386984 to calculate USD/MWh from USD/MMBtu.

A.2 Liquid based process (Carbon Engineering-like), electricity from grid, gas fueled calciner	223	210	247

Table 18 – Abatement costs with alternative electricity and gas prices, USD/ton CO_2

Operational costs (other than energy)

As the estimated operational costs are associated with a great amount of uncertainty, we test the sensitivity of the calculated abatement costs with a 50 per cent change in operational costs compared to the baseline assumption. The energy costs are kept constant.

The analysis shows that abatement costs are relatively sensitive to changes in operational costs. A 50 per cent increase/decrease in operational costs increases/reduces the abatement costs by around 10 per cent in case A and 27 per cent in case B. Operational costs is the most critical assumption to abatement costs in case B, as operational costs (excluded energy) make up approx. 35 per cent of the total costs. The three major components regarding operational costs for the hypothetical plant using the liquid-based process (case A) are the pellet reactor, air contactor and the CO_2 compressor (see Figure 35). Abatement costs for different scenarios are presented in Table 19.

Case	Baseline	Low (-50%)	High (+50%)
A.1 Liquid based process (Carbon Engineering-like), fully powered by gas	223	199	247
A.2 Liquid based process (Carbon Engineering-like), electricity from grid, gas fueled calciner	216	192	239
B.1 Adsorbent based process (Climeworks-like) with heat pump	385	282	488

Table 19 – Abatement costs with different operational cost assumptions, USD/ton CO_2

Investment costs

The assumed investment costs are also associated with a great amount of uncertainty, and we test the sensitivity of the calculated abatement costs with the same changes as we did for operational costs. The sensitivity analysis, with results presented in Table 20, shows that a 50 per cent increase/reduction in investment cost increases/reduces the calculated abatement costs for case A by more than 20 per cent, making it the most critical assumption for the hypothetical plant in Øygarden (case A). For the hypothetical plant in Mosjøen (case B), a 50 per cent change in investment costs increases/reduces the calculated abatement costs by almost 20 per cent.

Case	Baseline	Low (-50%)	High (+50%)
A.1 Liquid based process (Carbon Engineering-like), fully powered by gas	223	173	274
A.2 Liquid based process (Carbon Engineering-like), electricity from grid, gas fueled calciner	216	165	266
B.1 Adsorbent based process (Climeworks-like) with heat pump	385	202	568

Table 20 – Abatement costs with different investment cost assumptions, USD/ton CO_2

Range for abatement costs for first-of-a-kind DAC plants

To summarize the sensitivity analysis: the calculated abatement costs for a **first-of-a-kind DAC plant** in Norway are associated with a great amount of uncertainty. Energy prices seem to have a relatively small effect on abatement costs within the most probable price scenarios for electricity and gas over the next thirty years in the two relevant Norwegian cases. However, assuming that the error of the estimated investment and operational cost may be 50 per cent, abatement costs may increase by 50 per cent in a pessimistic scenario with high energy prices, investment and operational costs. Similarly, in a more optimistic scenario, the abatement costs may be reduced by fifty percent. The outcome space for abatement costs reflects the uncertainty in estimated investment and operational costs of DAC plants today (Table 21).

Case	Baseline	Low	High
A.2 Liquid based process (Carbon Engineering-like), electricity from grid, gas fueled calciner	216	107	314
B.1 Adsorbent based process (Climeworks-like) with heat pump	385	202	568

Table 21 – Abatement costs for different scenarios, USD/ton CO_2

Figure 36 shows the outcome space for abatements costs for a first-of-a-kind DAC plant of the two types. The solid line shows our base case, while the high and low estimates are indicated by the blue columns.

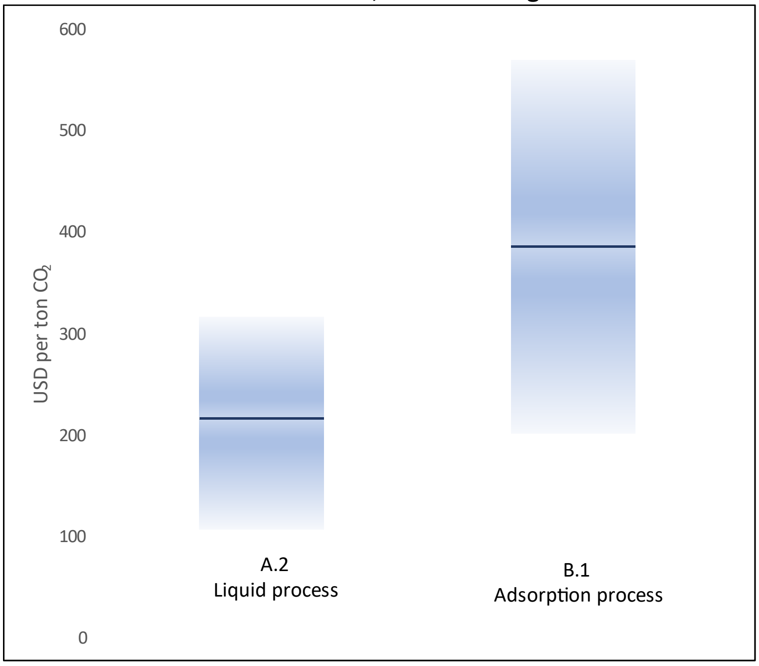

Figure 36 – Range for abatement cost with first-of-a-kind DAC plant in Norway, USD/ton CO_2

Range for abatement costs for nth of a kind DAC plants

In chapter 3 we discussed the learning curve and cost reductions from first to n^{th} of a kind DAC plant. Based on literature review, we expect a significant cost reduction from first-of-a-kind (FOAK) to n^{th} of a kind (NOAK) plant. The expected cost reductions range from 27 to 85 per cent in the literature. Investment and capital expenses are expected to decrease most, with energy, utilities and labour costs limiting the reduction in operational costs. With an overall reduction in total costs excl. energy cost of 27 to 85 per cent, abatement cost for base case n^{th} of a kind DAC plant may be as low as 90-175 USD/ton CO_2 with the hypothetical A.2 plant in Øygarden (using the liquid-based technology) and 90-290 USD/t CO_2 for the hypothetical B.1 plant in Mosjøen (using an adsorption-based technology). Figure 37 shows both the range for abatement costs for the n[th] of a kind DAC plants, together with the costs of the 1[st]-of-a-kind plants.

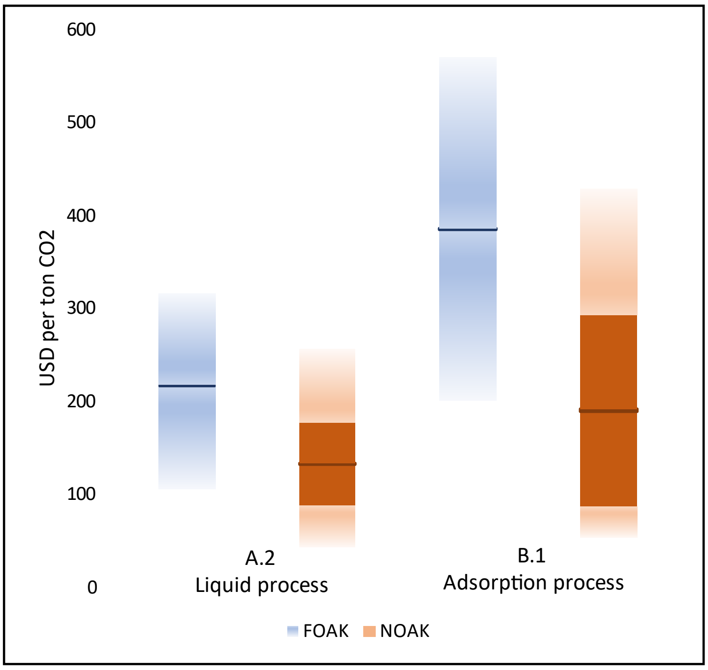

Figure 37 – Range for abatement cost with first (FOAK) and n[th] of a kind (NOAK) DAC plants in Norway, USD/ton CO_2

Note: The costs for B.1 are calculated assuming 1 mill. ton CO_2; costs for a plant of 100 000 ton CO_2 are about 10 per cent higher.

Comparing DAC to other abatement possibilities in Klimakur 2030

While our calculated abatement costs for the hypothetical cases are around 220 USD/t_{CO2} with the Carbon Engineering like process, and approximately 385 USD/t_{CO2} with the Climeworks-like process in the baseline scenario, they might increase to 315 USD/ton CO_2 and 570 USD/ton CO_2, respectively. All these estimates are greater than current and historic prices of emission quotas in EU Emissions Trading System (EU ETS), as well as the Norwegian CO_2-tax for sectors not covered by the ETS.

Comparing the calculated abatement costs for the hypothetical DAC plants to other CCS-technologies from Klimakur 2030, the abatement costs associated with DAC are higher. However, there are measures in Klimakur 2030 that have similar abatement costs as the hypothetical DAC plants, and DAC plants would be categorized in cost category 3, with abatement costs above 1500 NOK/ton CO_2 (see Figure 38). Abatement measures in this category are typically associated with immature technologies. Klimakur 2030 states, however, that there may be additional benefits attached to these technologies, but that these additional effects are hard to quantify and therefore not included in the abatement costs.

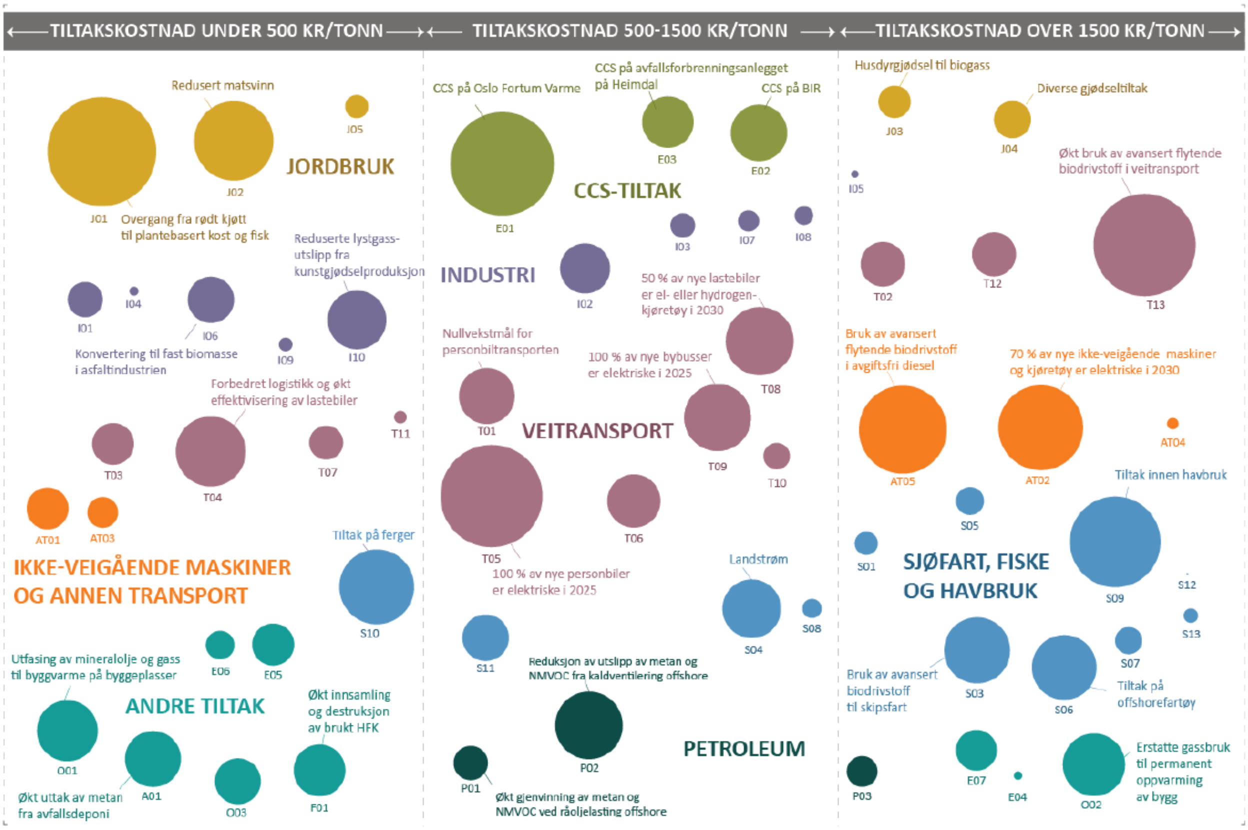

Figure 38 – Abatement costs ("tiltakskostnader") in Klimakur 2030

How to overcome barriers to DAC development?

DAC may play a greater role in achieving the carbon-neutral society in the future. As discussed above, the costs of removing CO_2 by DAC are higher than many other abatement measures available in Norway, but not prohibitively high. DAC would also contribute to *net removal* of CO_2.

At present, high capital costs, together with the uncertainty about how the technology will perform in "real life", seems to be the greatest concern. However, the main obstacle to large-scale development seems to be the lack a market for the "product" of the DAC plants – the CO_2 removed. Today, there is no market for the CO_2 removal credits: industries that are part of the EU ETS cannot use credits from a DAC plant at the EU ETS market; similarly, the non-ETS industries must still pay the CO_2 tax for their actual emissions, regardless of the CO_2 removal credits. Hence, nobody has any real incentive to buy the credits (other than for reporting in the companies' ESG reports). Notably, there is some voluntary trade in the credits, e.g., Climeworks has sold credits for 10 000 NOK/ton. However, the volumes are small, and do not provide sufficient certainty to companies to invest in an installation that will run for 20+ years.

If a market is created for the DAC credits, it will be the market that "chooses" the future technology, not the civil servants or politicians. Investors must still take the investment decisions and carry the risk of the investment. Hence, development of a market for DAC credits would be a better way to promote DAC technologies than subsidies or public investments.

DAC (and net removal technologies in general) is still an immature technology. Hence, supporting more research and testing that would contribute to bringing down the costs would also be appropriate.

8. Indirect Ocean Capture

The removal of CO_2 from oceanwater and other natural waters, or indirect ocean capture (IOC), sometimes the term direct ocean capture (DOC) is used, is one method of capturing dispersed CO_2. IOC also has the potential for offshore deployment that offers a variety of useful potential benefits such as reducing competition for useful land, allowing access to oceanic CO_2 storage sites currently only reachable by pipeline, and producing valuable CO_2 streams offshore for a number of potential uses. Finally, IOC represents a direct reversal of ocean acidification caused by anthropogenic CO_2 emissions.

This is technology is in its infancy and at technology readiness level 2 or possibly 3.

The ocean absorbs approximately 30 percent of the CO_2 that is released into the atmosphere. The absorption of CO_2 leads to a decrease in the pH (increase in acidity) of ocean water by formation of carbonic acid and bicarbonates. This affects marine life in several ways, including the formation of the carapace of decapods and shell of molluscs.

The CO_2 concentration in freshwater and seawater in contact and near equilibrium with the atmosphere is very low. The low concentration makes it difficult and energy intensive to capture CO_2. There is a high level of dissolved minerals in sea water caused by weathering over thousands and millions of years. Due to this the pH of seawater is around 8.3 and the CO_2/bicarbonate balance results in most of the CO_2 absorbed in seawater is in the form of bicarbonate (HCO_3^-). By acidifying the seawater, the bicarbonate is turned into dissolved CO_2. And it will be less energy intensive to release the CO_2 from the water.

Digdaya et al. [108] has tested a bipolar membrane (BPM) to first acidify oceanwater, extracting CO_2 and then return the water to the other side of the membrane, cf. Figure 39, where the pH of the oceanwater will increase to close to the original pH.

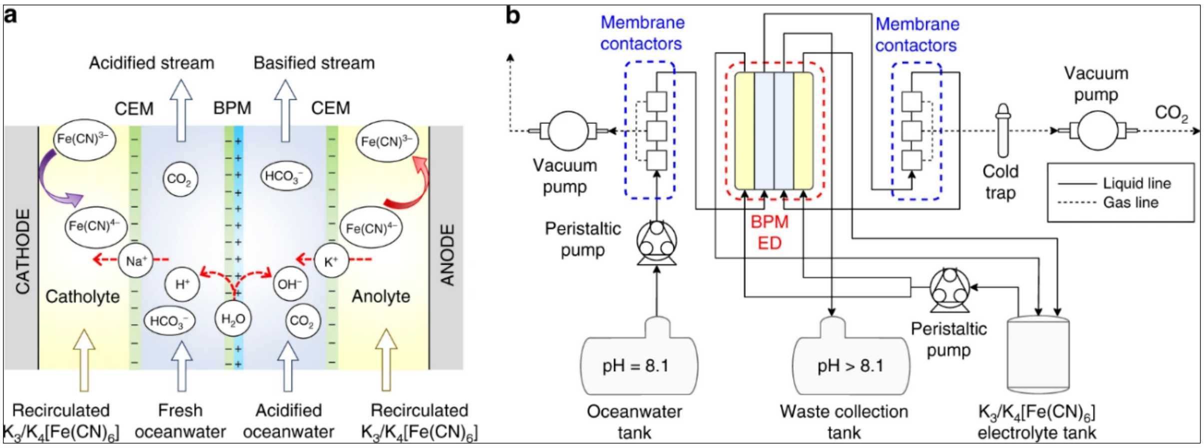

Figure 39 Schematic illustration and the BPM electrodialysis and CO_2 capture system (Picture reproduced fromDigdaya et al., A direct coupled electrochemical system for capture and conversion of CO2 from oceanwater, Nature Communications, 11, 2020, under Creative Commons Attribution License CC BY 4.0)

Sea water has a variable composition depending on temperature and depth. Typically values for inorganic carbon species are (from Dickson [109]):

- Dissolved CO_2 gas 0.682 g/ton
- Bicarbonate (HCO_3^-) 83 g/ton
- Carbonate ($CO_3^=$) 7.0 g/ton

Bicarbonate and carbonate will be converted to CO_2 if the water is acidified so in theory, it would be possible to capture 90.6 g CO_2 from one ton of sea water. Such an acidification is not practical and let us assume as an example that it would be possible to capture 50 % of this.

Example 1: Capturing only dissolved CO_2 gas, 0.682 g/ton

To capture 100 000 ton_{CO2}/y it would be needed to process 392 million ton water per day, equivalent to 4540 ton/s, which is more than six times the average flow of Norway's largest river Glomma (705 ton/s).

Example 2: Capturing 50 % of total carbon species, 90.6 g/ton as CO_2.

To capture 100 000 ton_{CO2}/y it would be needed to process 2.9 million ton water per day, equivalent to 34 ton/s, which is approximately five percent of the average flow of Norway's largest river Glomma.

Yan et al. [110] has proposed an alternative electrochemical hydrogen-looping system using a proton exchange membrane and a sodium exchange membrane instead of the bipolar membrane. It is claimed that this process needs less electricity for the acidification but is has the same general challenges as listed below. The sea water to be treated is in this process split in two streams, and CO_2 is only extracted from one of them, increasing the volume of water that need to be pumped.

There are also technical challenges with any IOC process that will have to be resolved:

- Oxygen and nitrogen gases dissolved in water must be separated from CO_2, either before or after CO_2 is transferred to the gas phase
- Fouling (biofilm formation, including growth of algae, mussels and other invertebrates) in equipment and on any membranes used. The membranes are especially susceptible as they may be clogged.
- Use of metals like platinum in electrodes or use of corrosion resistant materials can be a cost and supply issue
- Deoxygenated water discharged to the sea in large volumes may lead to anoxic sones, reduced biodiversity and formation of toxic H_2S.

IOC is thus a technology in infancy and much less mature than DAC. IOC needs to be tested in small pilot scale under realistic conditions with natural ocean waters. A technoeconomic analysis is premature given the status. The possible impact of processing large volumes of water on natural life and biodiversity will most likely limit the number of locations suitable for IOC.

A.1 Scaling-up and learning rate

As mentioned, the DAC costs are expected to decrease, and several factors contribute. By neglecting contingencies such as the need to deploy NET and reduce process carbon footprint, scaling-up and learning rate are beneficial to the economy of scale. The learning rate refers to the capacity in accumulating knowledge about a specific technology. The increment in the knowledge allows to reduce the uncertainties and be more confident in scaling-up procedures. The scaling-up paths the opportunity to the industrial deployment of the technology. When large scales are achieved, the economy of scale effects starts to positively impact on the economics. Currently, to reach the mega- and then the giga-tons scale of annual removal required by mid-century [83], DAC technologies must be deployed at unprecedented rates. A wide range of hardware technologies are known to have fallen in cost significantly over time. Many researchers have proposed reasons for their studies justified with the learning curve pattern of cost reduction (also called an experience curve) in which the cost of producing the next unit of a technology falls as a function of the total cumulative produced amount. This phenomenon is called learning-by-doing Figure 40 shows the results of applying the one-factor learning curve to solid sorbent DAC levelized costs for 'fast' (20%) and 'slow' (10%) LRs, with only capital costs experiencing reduction through learning-by-doing. An immediate conclusion is that cost projections depend strongly on the LR: costs fall to 200 USD/t_{CO2} after approximately 7 doublings (fast learning) or 14 doublings (slow learning), both of which are within the giga-tons scale required by mid-century.

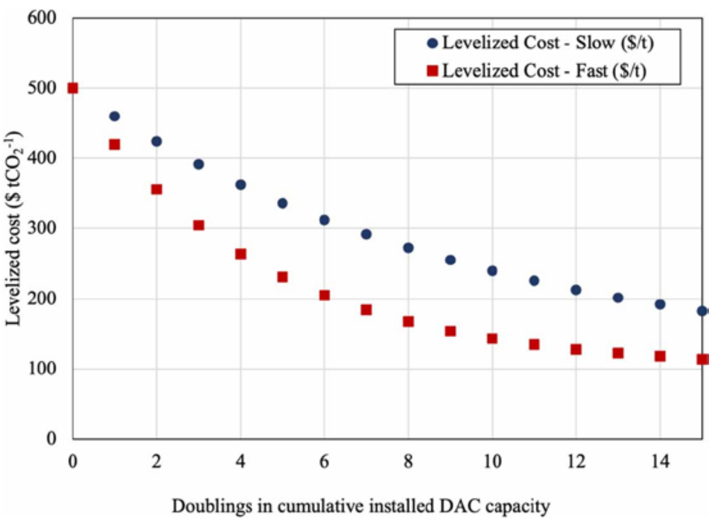

Figure 40 - Projected levelized cost of DAC as a function of the number of doublings in the cumulative installed DAC capacity (in t_{CO2}/y). Levelized cost is the sum of lifetime capital and operating costs divided by the lifetime tons removed (picture reproduced from McQueen et al., A review of direct air capture (DAC): scaling up commercial technologies and innovating for the future, 2021, Prog. Energy 3 032001 under Creative Commons Attribution License CC BY 4.0)

A closely related conclusion is that if DAC technology is observed to have a relatively high/fast LR, it could reach levelized costs of 150 USD/t_{CO2} after ten doublings of the cumulative capacity. However, these results are also highly dependent on the actual cost of production at the current level of deployment of DAC. If the current levelized cost is 400 USD/t_{CO2}, costs fall to 150 USD/t_{CO2} after 7 doublings in cumulative capacity (fast learning) or 15 doublings in cumulative capacity (slow learning). These actual costs are not directly observable outside of the companies producing DAC systems (prices may serve as a partial proxy for cost under some circumstances) and they are not generally reported in a transparent fashion by DAC companies. The learning-by-doing model does not account for potential limitations to the technology deployment such as energy crisis, materials shortage, and other unpredictable events. Additionally, the assumption of fixed operating costs (primarily due to energy consumption) limits the possible learning in this model. Therefore, near-term policy support for the installation of DAC facilities is likely to lead to rapid cost reductions and should therefore be given high priority. What here presented is also outlined in Figure 41 where it is possible to appreciate the positive effect of technology deployment, plant size and global capacity, and learning rate (learning-by-doing) on the reduction of the capital investments. The operational costs cannot be accounted because affected by locations and unpredictable oscillations.

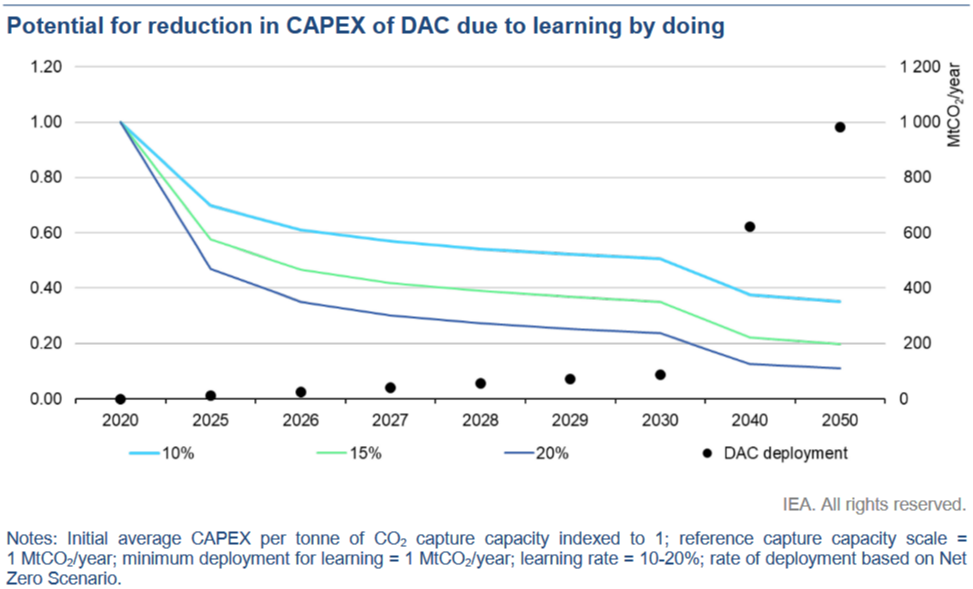

Figure 41 – Potential for the reduction in CAPEX of DAC due to learning by doing (picture reproduced with permission from the International Energy Agency, Direct Air Capture – A key technology for net zero, IEA report, 2022, all rights reserved)

The historical trend for the piloting capacity of DAC technologies is correlated with the learning rate. That means that a progressive increment of the size should correspond to an increment in the knowledge of the plant, its features, and the possibility of fast scaling-up. Climeworks is the only company showing a "normal" learning rate curve (Figure 42 and Figure 43) as suggested in suggested in [48,69,70]. A normal learning curve should present a progressive (but not necessarily linear) trend which is reflected in a similar trend in the capacity of the technology during its development. Climeworks started with a small module 900 t_{CO2}/y 2017 and now its ambitious is to operate a 36 000 t_{CO2}/y size DAC in Mammoth project by 2023. In six years, Climeworks tested different scales and the size increment looks coherent (Figure 43) and it is expected to achieve 400 000 t_{CO2}/y by 2025 and 1 mill. t_{CO2}/y by 2028 (if Climework aims at reaching such a large-scale). Conversely, the same concept does not apply for Carbon Engineering and Global Thermostat. Their learning rates appear fragmented and inhomogeneous. Carbon Engineering tested a very small scale for liquid-DAC (9 t_{CO2}/y) between 2015-2017 and now it is piloting a large plant of 1 mill. t_{CO2}/y (under construction and operative in 2026), similarly, Global Thermostat validated modules for 10 000 t_{CO2}/y (one hundred times the first Climework's module) in 2013 as first pilot campaign and now it would implement a large size DAC facility (100 000 t_{CO2}/y) by 2025. For both there is not information about intermediate piloting and scaling up activities from data merged from Sovacool et al. [91] and Ozkan et al. [82].

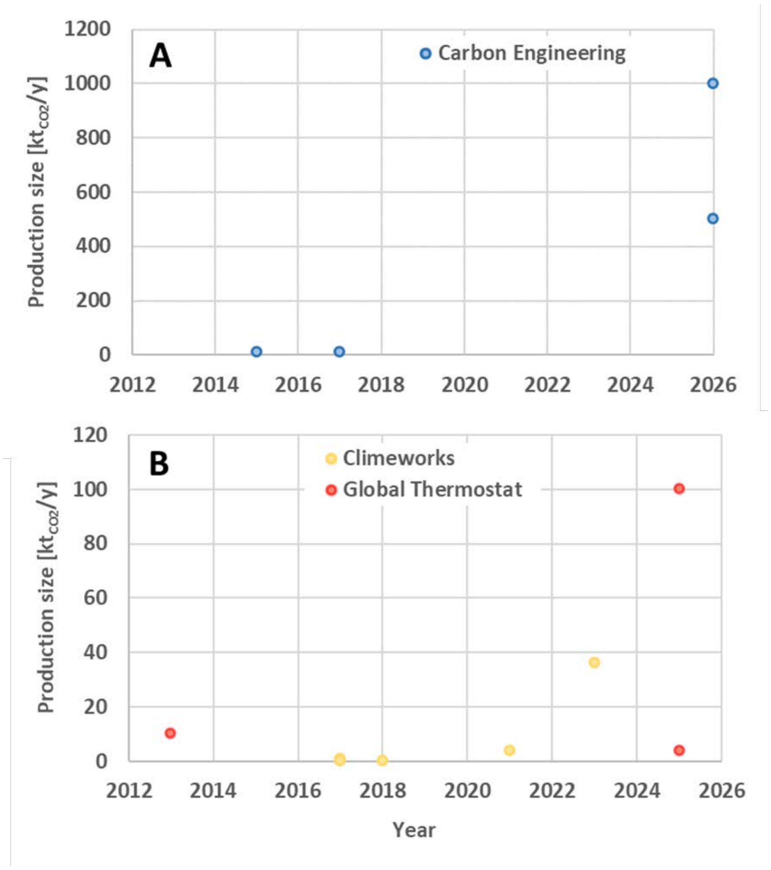

Figure 42 – Production size for pilot plants and planned DAC facilities for Carbon Engineering (A), Climeworks and Global Thermostat (B) using data or information gathered in Table 22

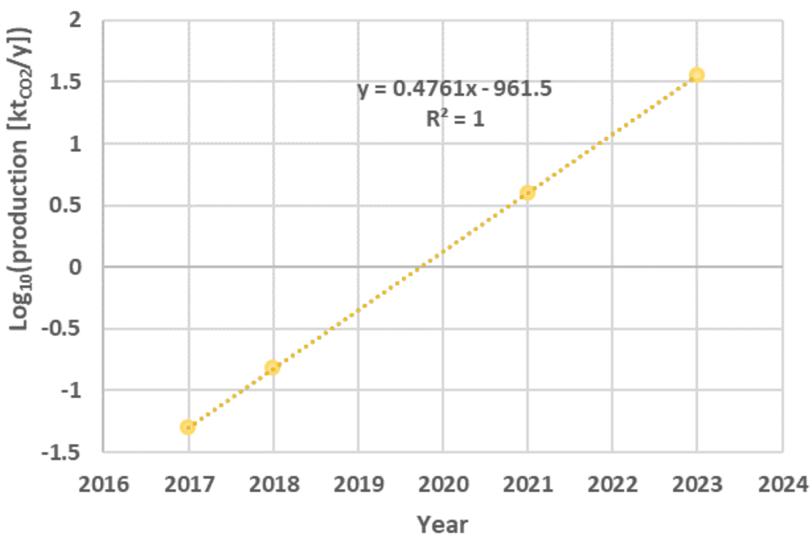

Figure 43 – Learning rate of Climeworks using data from Table 23 and evolution of the piloting scale during time (log-scale y-axis)

A.2 FOAK and NOAK difference

The benefit of the learning rate and scale up are graphically evident comparing Figure 44 (FOAK) with Figure 45 (NOAK) under different scenarios. The possibility of large-scale facility deployment progressively reduces the costs associated with material and equipment (blue bar). Even in the same time scenario, the economy of scale benefits (for instance, CAPEX for megaton scale is lower than kilotons one regardless the NOAK or FOAK classification). The large request of energy in DAC plants could also force nations to improve the energy distribution, but also intensify and grow the net energy production. A larger deployment grid will be reflected also in lower operation costs (dark green bar) according to IEA.

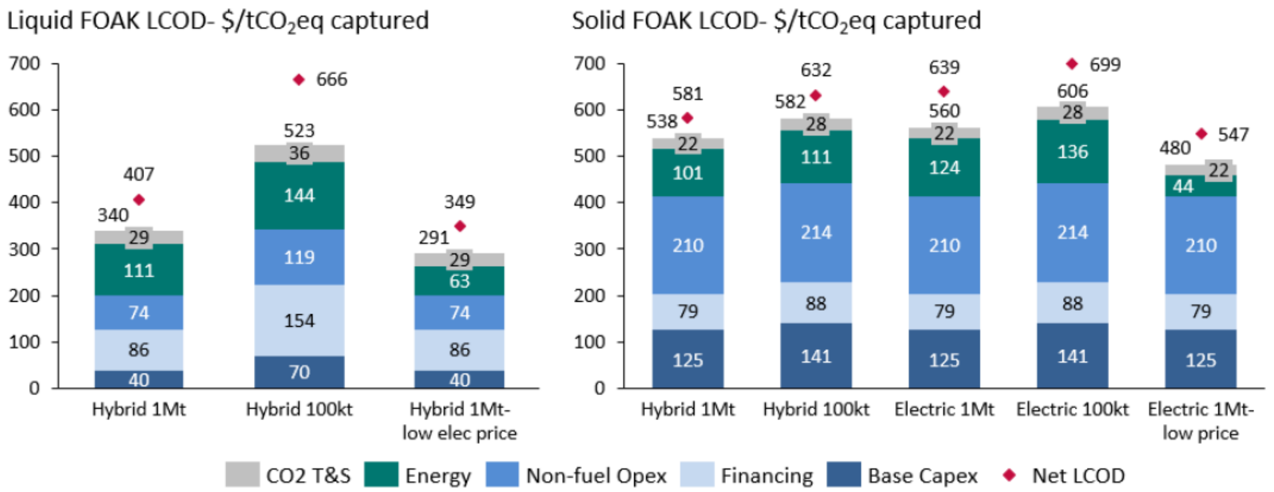

Figure 44 – Gross and net costs of different FOAK liquid and solid DAC configurations under different scenarios (picture reproduced with the permission from Element Energy's and IEAGHG report, Global Assessment of Direct Air Capture Costs, 2021)

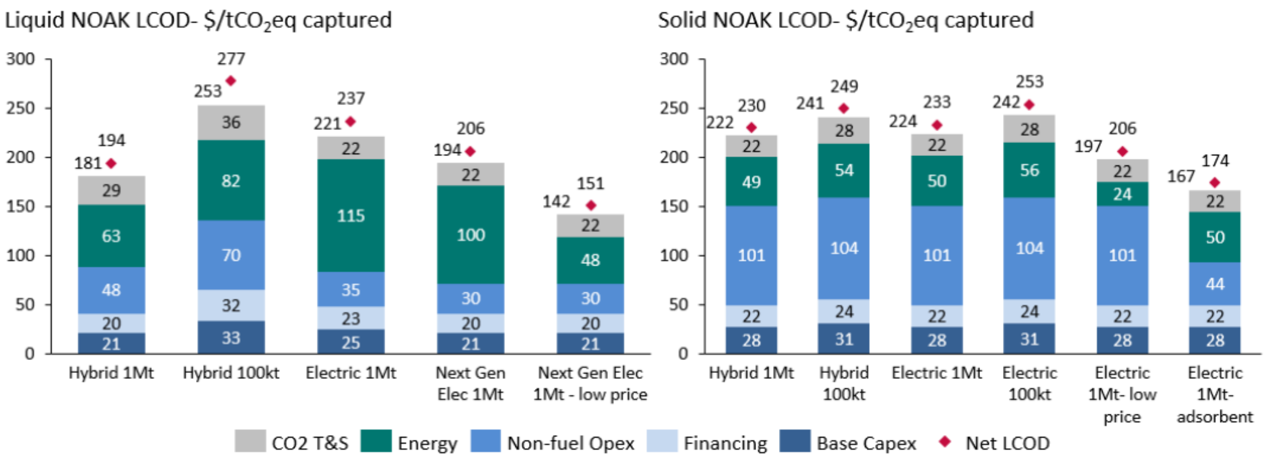

Figure 45 – Gross and net costs of different NOAK liquid and solid DAC configurations under different scenarios (picture reproduced with the permission from Element Energy's and IEAGHG report, Global Assessment of Direct Air Capture Costs, 2021)

A.3 Costs breakthrough

Hypothetical case A.1 – gas as energy source for turbine and calciner

Table 24 Capital expenditure, CAPEX, for a 1 mill. t_{CO2}/y plant based on liquid absorption. Only natural gas as energy source

	EC (equipment cost)	MC (material cost)	LC (labour cost)	TDFC (total direct field cost)	Indirect field cost	Total field cost	Engineering	Other project cost	Contingency	Sum field and non field cost	Lang factor
Air contactor	114,2	48	50	212,2	26,92	239,12	38,63	14,66	47,81	340,21	2,98
Pellet reactor	76,9	28,4	25,5	130,8	16,59	147,39	23,81	9,04	29,47	209,71	2,73
Calciner slaker	43,8	18,1	15,8	77,7	9,86	87,56	14,14	5,37	17,51	124,57	2,84
ASU	38	0	16,3	54,3	6,89	61,19	9,88	3,75	12,23	87,06	2,29
CO2 compressor	17,2	1,4	1,4	20	2,54	22,54	3,64	1,38	4,51	32,07	1,86
Steam unit	6,7	0,4	0,4	7,5	0,95	8,45	1,37	0,52	1,69	12,02	1,79
Power plant (NG)	32,7	0,9	1,4	35	4,44	39,44	6,37	2,42	7,89	56,11	1,72
Fines filter	17,6	7,1	6,2	30,9	3,92	34,82	5,62	2,13	6,96	49,54	2,81
Other equipm	96,9	3,4	2,5	102,8	13,04	115,84	18,71	7,1	23,16	164,82	1,7
Buildings	2,5	0	4,2	6,7	0,85	7,55	1,22	0,46	1,51	10,74	4,3
Transformer	0	18,6	1,2	19,8	2,51	22,31	3,6	1,37	4,46	31,74	
Sum	446,5	126,3	124,9	697,7	88,51	786,21	126,99	48,2	157,2	1118,59	2,5

Table 25 Operational expenditure, OPEX and yearly CAPEX, for a 1 000 000 t_{CO2}/y plant based on liquid absorption. Only natural gas as energy source.

	Electric power	NG	Process water	Cooling water	CaC03 makeup	CaC03 disposal	Manning	Mainte-nance	Total OPEX	Yearly CAPEX	Total costs per year	Per ton captured	Per ton avoided
Air contactor		0	0	0	0	0	1,34	13,61	14,95	33,9	48,85	33,58	50,03
Pellet reactor		0	0	0	8,9	8,9	0,82	8,39	27,08	20,9	47,98	32,98	49,15
Calciner slaker		32,6	0	0	0	0	0,49	4,98	38,08	12,41	50,49	34,71	51,72
ASU		0	0	0	0	0	0,34	3,48	3,82	8,68	12,5	8,59	12,80
C02 compressor		0	9,8	0	0	0	0,13	1,28	11,18	3,2	14,37	9,88	14,72
Steam turbine		0	0	0	0	0	0,05	0,48	0,53	1,2	1,73	1,19	1,77
Power plant		15,3	0	0	0	0	0,22	2,24	17,8	5,59	23,39	16,08	23,95
Fines filter		0	0	0	0	0	0,19	1,98	2,18	4,94	7,11	4,89	7,28
Other equipment		0	0	0	0	0	0,65	6,59	7,24	16,42	23,66	16,27	24,24
Buildings		0	0	0	0	0	0,04	0,43	0,47	1,07	1,54	1,06	1,57
Transformer		0	0	0	0	0	0,12	1,27	1,39	3,16	4,56	3,13	4,67
Sum		47,94	9,77	0,00	8,94	8,94	4,40	44,73	124,72	111,47	236,18	162,36	241,89

Hypothetical case B

The case is based on the following information/assumptions:

Variable	Value - unit of measure	Notes
Capacity	100 kt_{CO2}/y	Our assumption
Land for DAC plant	0.15 km^2	IEA report
Cost CO_2/t (First of a kind plant)	600 USD/t_{CO2}	IEAGHG report / Climeworks ORCA
CAPEX as percentage of cost	0.33 %	IEAGHG report
Energy use in (GJ)		
- Electricity	0.825 GJ/t_{CO2}	Aligned with NASEM report
- Thermal	4.1 GJ/t_{CO2}	Aligned with NASEM report
COP factor heat pump	3	1 kWh electricity gives 3 kWh heat

Calculated Case B1 – heat pump is used to reach the necessary temperature for desorption of CO_2. Waste heat is used free of cost.

Variable	Value - unit of measure	Notes
Energy use in (MWh)		
- Electricity	0.229 MWh/t_{CO2}	
- Thermal	1.14 MWh/t_{CO2}	
- Electricity for heat pump	1.14 : 3 = 0.38 MWh/t_{CO2}	Heat pump COP = 3 (average value)
Total electricity consumption	0.609 MWh/t_{CO2}	For full year 61 GWh, effect 6.9 MW
Factor for converting yearly Capex to invested Capex	10	Our assumption, interest 7.5% and 2 year building time and 23 years operation
CAPEX yearly	20 mill USD	Aligned with NASEM report
CAPEX invested	200 mill USD	

Calculated Case B2 – electricity is used to supply the necessary temperature for desorption of CO_2. No use of waste heat.

Variable	Value - unit of measure	Notes
Energy use in (MWh)		
- Electricity	0.229 MWh/t_{CO2}	
- Thermal	1.14 MWh/t_{CO2}	
Total electricity consumption	1.37 MWh/t_{CO2}	For full year 137 GWh, effect 15.6 MW
Factor for converting yearly Capex to invested Capex	10	Our assumption, interest 7.5% and 2 year building time and 23 years operation
CAPEX yearly	20 mill USD	Aligned with NASEM report
CAPEX invested	200 mill USD	
Note that investment in heat pumps is avoided, but larger infrastructure and a heating system will be needed.		

Comparison of CAPEX for case A and B

An estimate of the CAPEX for a 1 Mt/y plant can be made to compare to the CAPEX of case B to case A.

The formula used is:

$$C_2 = C_1 \cdot \left(\frac{Q_2}{Q_1}\right)^x$$

Where:

C_1 = CAPEX case B = 200 mill USD, Q_1 = capacity case B = 100 000 t/y

Q_2 = capacity case A = 1 000 000 t/y

Exponent x is scaling factor, 0.9, as the process is dependent on parallel, modular contactors.

C_2 = 1589 mill USD for 1 Mt/y CO_2 (net capture) with solid adsorbent.

As there is a large uncertainty on the cost of DAC technologies, it is not possible to say at this stage of technology development that there is significant difference between solid and liquid technologies, case A and B, with regard to CAPEX, 1119 and 1589 mill USD respectively for a 1 Mt plant.

9. Relevant and essential references on DAC

Underlined references are of relevance for governmental agencies and policies makers (many are open access)

Review and general aspects on the DAC

1. Global Assessment of Direct Air Capture Costs, IEAGHG, 2021. http://documents.ieaghg.org/index.php/s/A8Qau09NMQQYgVL.
2. Direct Air Capture 2022 A key technology for net zero, IEA, 2022. https://www.iea.org/reports/direct-air-capture-2022.
3. K.Z. House, A.C. Baclig, M. Ranjan, E.A. van Nierop, J. Wilcox, H.J. Herzog, Economic and energetic analysis of capturing CO_2 from ambient air, Proc. Natl. Acad. Sci. 108 (2011) 20428–20433. https://doi.org/10.1073/pnas.1012253108.
4. National Academies of Sciences Engineering, Medicine, Negative Emissions Technologies and Reliable Sequestration: A Research Agenda, The National Academies Press, Washington, DC, 2019. https://doi.org/10.17226/25259.
5. E.S. Sanz-Pérez, C.R. Murdock, S.A. Didas, C.W. Jones, Direct Capture of CO2 from Ambient Air, Chem. Rev. 116 (2016) 11840–11876. https://doi.org/10.1021/acs.chemrev.6b00173.

Essential on techno-economic assessment (TEA) aspects

1. Direct Air Capture 2022 A key technology for net zero, IEA, 2022. https://www.iea.org/reports/direct-air-capture-2022.
2. Global Assessment of Direct Air Capture Costs, IEAGHG, 2021. http://documents.ieaghg.org/index.php/s/A8Qau09NMQQYgVL.
3. National Academies of Sciences Engineering, Medicine, Negative Emissions Technologies and Reliable Sequestration: A Research Agenda, The National Academies Press, Washington, DC, 2019. https://doi.org/10.17226/25259
4. N. McQueen, K.V. Gomes, C. McCormick, K. Blumanthal, M. Pisciotta, J. Wilcox, A review of direct air capture (DAC): scaling up commercial technologies and innovating for the future, Prog. Energy. 3 (2021) 032001. https://doi.org/10.1088/2516-1083/abf1ce
5. J. Young, N. McQueen, C. Charalambous, S. Foteinis, O. Hawrot, M. Ojeda, H. Pilorgé, J. Andresen, P. Psarras, P. Renforth, S. Garcia, M. van der Spek, The cost of direct air capture and storage: the impact of technological learning, regional diversity, and policy., Chemistry, 2022. https://doi.org/10.26434/chemrxiv-2022-dp36t-v2

Essential elements on DAC LAC (overview)

1. R. Chauvy, L. Dubois, Life cycle and techno-economic assessments of direct air capture processes: An integrated review, Int. J. Energy Res. 46 (2022) 10320–10344. https://doi.org/10.1002/er.7884.

Policy for DAC

1. N. McQueen, K.V. Gomes, C. McCormick, K. Blumanthal, M. Pisciotta, J. Wilcox, A review of direct air capture (DAC): scaling up commercial technologies and innovating for the future, Prog. Energy. 3 (2021) 032001. https://doi.org/10.1088/2516-1083/abf1ce
2. J. Young, N. McQueen, C. Charalambous, S. Foteinis, O. Hawrot, M. Ojeda, H. Pilorgé, J. Andresen, P. Psarras, P. Renforth, S. Garcia, M. van der Spek, The cost of direct air capture and storage: the impact of technological learning, regional diversity, and policy., Chemistry, 2022. https://doi.org/10.26434/chemrxiv-2022-dp36t-v2
3. B.K. Sovacool, C.M. Baum, S. Low, C. Roberts, J. Steinhauser, Climate policy for a net-zero future: ten recommendations for Direct Air Capture, Environ. Res. Lett. 17 (2022) 074014. https://doi.org/10.1088/1748-9326/ac77a4.
4. Global Assessment of Direct Air Capture Costs, IEAGHG, 2021. http://documents.ieaghg.org/index.php/s/A8Qau09NMQQYgVL.
5. Direct Air Capture 2022 A key technology for net zero, IEA, 2022. https://www.iea.org/reports/direct-air-capture-2022

10. References

[1] E.S. Sanz-Pérez, C.R. Murdock, S.A. Didas, C.W. Jones, Direct Capture of CO2 from Ambient Air, Chem. Rev. 116 (2016) 11840–11876. https://doi.org/10.1021/acs.chemrev.6b00173.

[2] M. Bui, C.S. Adjiman, A. Bardow, E.J. Anthony, A. Boston, S. Brown, P.S. Fennell, S. Fuss, A. Galindo, L.A. Hackett, J.P. Hallett, H.J. Herzog, G. Jackson, J. Kemper, S. Krevor, G.C. Maitland, M. Matuszewski, I.S. Metcalfe, C. Petit, G. Puxty, J. Reimer, D.M. Reiner, E.S. Rubin, S.A. Scott, N. Shah, B. Smit, J.P.M. Trusler, P. Webley, J. Wilcox, N. Mac Dowell, Carbon capture and storage (CCS): the way forward, Energy Environ. Sci. 11 (2018) 1062–1176. https://doi.org/10.1039/C7EE02342A.

[3] K.S. Lackner, S. Brennan, J.M. Matter, A.-H.A. Park, A. Wright, B. van der Zwaan, The urgency of the development of CO_2 capture from ambient air, Proc. Natl. Acad. Sci. 109 (2012) 13156–13162. https://doi.org/10.1073/pnas.1108765109.

[4] M.D. Eisaman, Negative Emissions Technologies: The Tradeoffs of Air-Capture Economics, Joule. 4 (2020) 516–520. https://doi.org/10.1016/j.joule.2020.02.007.

[5] C. Breyer, Direct Air Capture of CO2: A Key Technology for Ambitious Climate Change Mitigation, (n.d.) 5.

[6] Global Assessment of Direct Air Capture Costs, IEAGHG, 2021. http://documents.ieaghg.org/index.php/s/A8Qau09NMQQYgVL.

[7] Direct Air Capture 2022 A key technology for net zero, IEA, 2022. https://www.iea.org/reports/direct-air-capture-2022.

[8] D.W. Keith, G. Holmes, D. St. Angelo, K. Heidel, A Process for Capturing CO2 from the Atmosphere, Joule. 2 (2018) 1573–1594. https://doi.org/10.1016/j.joule.2018.05.006.

[9] National Academies of Sciences Engineering, Medicine, Negative Emissions Technologies and Reliable Sequestration: A Research Agenda, The National Academies Press, Washington, DC, 2019. https://doi.org/10.17226/25259.

[10] R.P. Wijesiri, G.P. Knowles, H. Yeasmin, A.F.A. Hoadley, A.L. Cha, Technoeconomic Evaluation of a Process Capturing CO2 Directly from Air, (2019) 23.

[11] C. Gebald, W. Meier, N. Piatkowski, T. Rüesch, J.A. Wurzbacher, Direct Air Capture Device, WO2015185434A1, 2015.

[12] J.A. Wurzbacher, C. Gebald, S. Brunner, A. Steinfeld, Heat and mass transfer of temperature–vacuum swing desorption for CO2 capture from air, Chem. Eng. J. 283 (2016) 1329–1338. https://doi.org/10.1016/j.cej.2015.08.035.

[13] G. Leonzio, P.S. Fennell, N. Shah, Analysis of Technologies for Carbon Dioxide Capture from the Air, Appl. Sci. 12 (2022) 8321. https://doi.org/10.3390/app12168321.

[14] Y. Ishimoto, M. Sugiyama, E. Kato, R. Moriyama, K. Tsuzuki, A. Kurosawa, Putting Costs of Direct Air Capture in Context, SSRN Electron. J. (2017). https://doi.org/10.2139/ssrn.2982422.

[15] M. Ozkan, Direct air capture of CO2: A response to meet the global climate targets, MRS Energy Sustain. 8 (2021) 51–56. https://doi.org/10.1557/s43581-021-00005-9.

[16] Greencap Solutions, (n.d.). https://greencap-solutions.com/captures-co2-from-the-air/ (accessed November 10, 2022).

[17] Greencap Solutions, (n.d.). https://greencap-solutions.com/direct-air-capture-dac-technology/ (accessed November 10, 2022).

[18] S. Ibrahim, CO2 capture by adsorption, Master thesis, uis, 2021. https://uis.brage.unit.no/uis-xmlui/handle/11250/2823473 (accessed November 10, 2022).

[19] A. Abaza, Direct air capture of CO2 by adsorption on zeolites, Master thesis, uis, 2021. https://uis.brage.unit.no/uis-xmlui/handle/11250/2799861 (accessed November 10, 2022).

[20] X. Mao, W. Tian, Y. Ren, G. Rutledge, T.A. Hatton, Adsorbents, Systems, and Methods for Separation of Organic Species from Water, WO2019006396A1, 2019.

[21] S. Voskian, T.A. Hatton, Faradaic electro-swing reactive adsorption for CO_2 capture, Energy Environ. Sci. 12 (2019) 3530–3547. https://doi.org/10.1039/C9EE02412C.

[22] Y. Liu, H.-Z. Ye, K.M. Diederichsen, T. Van Voorhis, T.A. Hatton, Electrochemically mediated carbon dioxide separation with quinone chemistry in salt-concentrated aqueous media, Nat. Commun. 11 (2020) 2278. https://doi.org/10.1038/s41467-020-16150-7.

[23] K.M. Diederichsen, T.A. Hatton, Nondimensional Analysis of a Hollow Fiber Membrane Contactor for Direct Air Capture, Ind. Eng. Chem. Res. 61 (2022) 11964–11976. https://doi.org/10.1021/acs.iecr.2c02206.

[24] J. Wilcox, An electro-swing approach, Nat. Energy. 5 (2020) 121–122. https://doi.org/10.1038/s41560-020-0554-4.

[25] A. Kiani, M. Lejeune, C. Li, J. Patel, P. Feron, Liquefied synthetic methane from ambient CO2 and renewable H2 - A technoeconomic study, J. Nat. Gas Sci. Eng. 94 (2021) 104079. https://doi.org/10.1016/j.jngse.2021.104079.

[26] A. Kiani, K. Jiang, P. Feron, Techno-Economic Assessment for CO2 Capture From Air Using a Conventional Liquid-Based Absorption Process, Front. Energy Res. 8 (2020) 92. https://doi.org/10.3389/fenrg.2020.00092.

[27] Robert Socolow, Michael Desmond, Roger Aines, Jason Blackstock, Olav Bolland, Tina Kaarsberg, Nathan Lewis, Marco Mazzotti, Allen Pfeffer, Karma Sawyer, Jeffrey Siirola, Berend Smit, Jennifer Wilcox, Direct Air Capture of CO2 with Chemicals A Technology Assessment for the APS Panel on Public Affairs, APS Society, 2011. https://www.aps.org/policy/reports/popa-reports/loader.cfm?csModule=security/getfile&PageID=244407.

[28] K.Z. House, A.C. Baclig, M. Ranjan, E.A. van Nierop, J. Wilcox, H.J. Herzog, Economic and energetic analysis of capturing CO_2 from ambient air, Proc. Natl. Acad. Sci. 108 (2011) 20428–20433. https://doi.org/10.1073/pnas.1012253108.

[29] R. Royce, Project ENCORE: direct air capture, (n.d.) 14.

[30] Press releases, (n.d.). https://www.rolls-royce.com/media/press-releases.aspx (accessed November 10, 2022).

[31] R. Numaguchi, T. Okumura, S. Nishibe, K. Yoshizawa, Y. Furushima, T. Nohara, M. Kato, A. Saito, T. Masuda, R. Hako, Y. Sato, N. Kanomata, K. Tanaka, Towards the Carbon Circulation Society: Direct Air Capture by Kawasaki CO2 Capture Technology and CO2 utilization, SSRN Electron. J. (2021). https://doi.org/10.2139/ssrn.3815348.

[32] M. Barth, Current Situation and Ongoing Projects on Carbon Capture and Storage and Carbon Capture and Utilization in Germany and Japan, (n.d.) 59.

[33] R. Numaguchi, T. Okumura, S. Nishibe, K. Yoshizawa, K. Tanaka, Direct air capture by Kawasaki CO2 Capture technology: demonstration at various atmospheric conditions using novel amine solid sorbent, in: GHGT-16 Abstr. Proc., n.d.: p. 3.

[34] F. Sabatino, M. Gazzani, F. Gallucci, M. van Sint Annaland, Modeling, Optimization, and Techno-Economic Analysis of Bipolar Membrane Electrodialysis for Direct Air Capture Processes, Ind. Eng. Chem. Res. 61 (2022) 12668–12679. https://doi.org/10.1021/acs.iecr.2c00889.

[35] F. Sabatino, M. Mehta, A. Grimm, M. Gazzani, F. Gallucci, G.J. Kramer, M. Van Sint Annaland, Evaluation of a Direct Air Capture Process Combining Wet Scrubbing and Bipolar Membrane Electrodialysis, Ind. Eng. Chem. Res. 59 (2020) 7007–7020. https://doi.org/10.1021/acs.iecr.9b05641.

[36] Our Technology, Mission Zero Technol. - Home News. (n.d.). https://www.missionzero.tech/our-technology (accessed November 17, 2022).

[37] Mission Zero-led consortium win £3M government contract to pilot breakthrough DAC technology, Mission Zero Technol. - Home News. (n.d.). https://www.missionzero.tech/news/mission-zero-led-consortium-win-3m-government-contract-to-pilot-breakthrough-dac-technology-7-2022 (accessed November 17, 2022).

[38] Skytree | Indoor Farming, Skytree. (n.d.). https://skytree.eu/greenhouse/ (accessed November 3, 2022).

[39] Technology, Infin. LLC. (n.d.). http://www.infinitreellc.com/technology (accessed November 3, 2022).

[40] J. Elfving, C. Bajamundi, J. Kauppinen, T. Sainio, Modelling of equilibrium working capacity of PSA, TSA and TVSA processes for CO 2 adsorption under direct air capture conditions, J. CO2 Util. 22 (2017) 270–277. https://doi.org/10.1016/j.jcou.2017.10.010.

[41] Direct Air Capture (DAC) appliances, Hydrocell Oy. (n.d.). https://hydrocell.fi/en/air-cleaners-carbon-dioxide-filters-and-dac-appliances/dac-appliances/ (accessed November 3, 2022).

[42] F.V. Vázquez, J. Koponen, V. Ruuskanen, C. Bajamundi, A. Kosonen, P. Simell, J. Ahola, C. Frilund, J. Elfving, M. Reinikainen, N. Heikkinen, J. Kauppinen, P. Piermartini, Power-to-X technology using renewable electricity and carbon dioxide from ambient air: SOLETAIR proof-of-concept and improved process concept, J. CO2 Util. 28 (2018) 235–246. https://doi.org/10.1016/j.jcou.2018.09.026.

[43] C. Jeong-Potter, M. Abdallah, C. Sanderson, M. Goldman, R. Gupta, R. Farrauto, Dual function materials (Ru+Na2O/Al2O3) for direct air capture of CO2 and in situ catalytic methanation: The impact of realistic ambient conditions, Appl. Catal. B Environ. 307 (2022) 120990. https://doi.org/10.1016/j.apcatb.2021.120990.

[44] M.A. Arellano-Treviño, N. Kanani, C.W. Jeong-Potter, R.J. Farrauto, Bimetallic catalysts for CO2 capture and hydrogenation at simulated flue gas conditions, Chem. Eng. J. 375 (2019) 121953. https://doi.org/10.1016/j.cej.2019.121953.

[45] S. Brandani, Carbon Dioxide Capture from Air: A Simple Analysis, Energy Environ. 23 (2012) 319–328. https://doi.org/10.1260/0958-305X.23.2-3.319.

[46] C. Pritchard, Thermodynamics, economics and systems thinking: What role for air capture of CO2?, Process Saf. Environ. Prot. (n.d.) 8.

[47] D. Krekel, R.C. Samsun, R. Peters, D. Stolten, The separation of CO2 from ambient air – A techno-economic assessment, Appl. Energy. 218 (2018) 361–381. https://doi.org/10.1016/j.apenergy.2018.02.144.

[48] N. McQueen, K.V. Gomes, C. McCormick, K. Blumanthal, M. Pisciotta, J. Wilcox, A review of direct air capture (DAC): scaling up commercial technologies and innovating for the future, Prog. Energy. 3 (2021) 032001. https://doi.org/10.1088/2516-1083/abf1ce.

[49] N. McQueen, P. Psarras, H. Pilorgé, S. Liguori, J. He, M. Yuan, C.M. Woodall, K. Kian, L. Pierpoint, J. Jurewicz, J.M. Lucas, R. Jacobson, N. Deich, J. Wilcox, Cost Analysis of Direct Air Capture and Sequestration Coupled to Low-Carbon Thermal Energy in the United States, Environ. Sci. Technol. 54 (2020) 7542–7551. https://doi.org/10.1021/acs.est.0c00476.

[50] F. Sabatino, A. Grimm, F. Gallucci, M. van Sint Annaland, G.J. Kramer, M. Gazzani, A comparative energy and costs assessment and optimization for direct air capture technologies, Joule. 5 (2021) 2047–2076. https://doi.org/10.1016/j.joule.2021.05.023.

[51] M. Sendi, M. Bui, N. Mac Dowell, P. Fennell, Geospatial analysis of regional climate impacts to accelerate cost-efficient direct air capture deployment, One Earth. 5 (2022) 1153–1164. https://doi.org/10.1016/j.oneear.2022.09.003.

[52] P. Eisenberger, Carbon Dioxide Capture/Regeneration Structures and Techniques, US2011041688A1, 2011.

[53] C. Beuttler, L. Charles, J. Wurzbacher, The Role of Direct Air Capture in Mitigation of Anthropogenic Greenhouse Gas Emissions, Front. Clim. 1 (2019) 10. https://doi.org/10.3389/fclim.2019.00010.

[54] US Patent Application for System and Method for Carbon Dioxide Capture and Sequestration Patent Application (Application #20200009504 issued January 9, 2020) -

Justia Patents Search, (n.d.). https://patents.justia.com/patent/20200009504 (accessed November 4, 2022).

[55] C. Breyer, M. Fasihi, A. Aghahosseini, Carbon dioxide direct air capture for effective climate change mitigation based on renewable electricity: a new type of energy system sector coupling, Mitig. Adapt. Strateg. Glob. Change. 25 (2020) 43–65. https://doi.org/10.1007/s11027-019-9847-y.

[56] J.B. Wevers, L. Shen, M. van der Spek, What Does It Take to Go Net-Zero-CO2? A Life Cycle Assessment on Long-Term Storage of Intermittent Renewables With Chemical Energy Carriers, Front. Energy Res. 8 (2020). https://www.frontiersin.org/articles/10.3389/fenrg.2020.00104 (accessed November 4, 2022).

[57] C. Arpagaus, F. Bless, M. Uhlmann, J. Schiffmann, S.S. Bertsch, High temperature heat pumps: Market overview, state of the art, research status, refrigerants, and application potentials, Energy. 152 (2018) 985–1010. https://doi.org/10.1016/j.energy.2018.03.166.

[58] X. Shi, H. Xiao, H. Azarabadi, J. Song, X. Wu, X. Chen, K.S. Lackner, Sorbents for the Direct Capture of CO2 from Ambient Air, Angew. Chem. Int. Ed. 59 (2020) 6984–7006. https://doi.org/10.1002/anie.201906756.

[59] X. Zhu, W. Xie, J. Wu, Y. Miao, C. Xiang, C. Chen, B. Ge, Z. Gan, F. Yang, M. Zhang, D. O'Hare, J. Li, T. Ge, R. Wang, Recent advances in direct air capture by adsorption, Chem. Soc. Rev. 51 (2022) 6574–6651. https://doi.org/10.1039/D1CS00970B.

[60] K. Madhu, S. Pauliuk, S. Dhathri, F. Creutzig, Understanding environmental trade-offs and resource demand of direct air capture technologies through comparative life-cycle assessment, Nat. Energy. 6 (2021) 1035–1044. https://doi.org/10.1038/s41560-021-00922-6.

[61] S. Deutz, A. Bardow, Life-cycle assessment of an industrial direct air capture process based on temperature–vacuum swing adsorption, Nat. Energy. 6 (2021) 203–213. https://doi.org/10.1038/s41560-020-00771-9.

[62] G. Holmes, D.W. Keith, An air–liquid contactor for large-scale capture of CO2 from air, Philos. Trans. R. Soc. Math. Phys. Eng. Sci. 370 (2012) 4380–4403. https://doi.org/10.1098/rsta.2012.0137.

[63] J. Gertner, The Tiny Swiss Company That Thinks It Can Help Stop Climate Change, N. Y. Times. (2019). https://www.nytimes.com/2019/02/12/magazine/climeworks-business-climate-change.html (accessed November 5, 2022).

[64] K.S. Lackner, H. Azarabadi, Buying down the Cost of Direct Air Capture, Ind. Eng. Chem. Res. 60 (2021) 8196–8208. https://doi.org/10.1021/acs.iecr.0c04839.

[65] G. Thermostat, Dr. Chichilnisky Gives Talk on Carbon Negative Power Plants and Their Impact on Environment - Puerto Madryn, Argentina 10/23, Glob. Thermostat. (2018). https://globalthermostat.com/2018/10/dr-chichilnisky-gives-talk-on-carbon-negative-power-plants-and-their-impact-on-environment-puerto-madryn-argentina-10-23/ (accessed November 4, 2022).

[66] A. Sinha, M.J. Realff, A parametric study of the techno-economics of direct CO2 air capture systems using solid adsorbents, AIChE J. 65 (2019) e16607. https://doi.org/10.1002/aic.16607.

[67] M. Mazzotti, R. Baciocchi, M.J. Desmond, R.H. Socolow, Direct air capture of CO2 with chemicals: optimization of a two-loop hydroxide carbonate system using a countercurrent air-liquid contactor, Clim. Change. 118 (2013) 119–135. https://doi.org/10.1007/s10584-012-0679-y.

[68] F. Zeman, Reducing the Cost of Ca-Based Direct Air Capture of CO2, Environ. Sci. Technol. 48 (2014) 11730–11735. https://doi.org/10.1021/es502887y.

[69] J. Young, N. McQueen, C. Charalambous, S. Foteinis, O. Hawrot, M. Ojeda, H. Pilorgé, J. Andresen, P. Psarras, P. Renforth, S. Garcia, M. van der Spek, The cost of direct air capture and storage: the impact of technological learning, regional diversity, and policy., Chemistry, 2022. https://doi.org/10.26434/chemrxiv-2022-dp36t-v2.

[70] S. Shayegh, V. Bosetti, M. Tavoni, Future Prospects of Direct Air Capture Technologies: Insights From an Expert Elicitation Survey, Front. Clim. 3 (2021) 630893. https://doi.org/10.3389/fclim.2021.630893.

[71] M. Fasihi, O. Efimova, C. Breyer, Techno-economic assessment of CO2 direct air capture plants, J. Clean. Prod. 224 (2019) 957–980. https://doi.org/10.1016/j.jclepro.2019.03.086.

[72] R. Pearce, The Swiss company hoping to capture 1% of global CO2 emissions by 2025, Carbon Brief. (2017). https://www.carbonbrief.org/swiss-company-hoping-capture-1-global-co2-emissions-2025/ (accessed November 5, 2022).

[73] E.S. Rubin, I.M.L. Azevedo, P. Jaramillo, S. Yeh, A review of learning rates for electricity supply technologies, Energy Policy. 86 (2015) 198–218. https://doi.org/10.1016/j.enpol.2015.06.011.

[74] M. Weiss, H.M. Junginger, M.K. Patel, Learning energy efficiency: experience curves for household appliances and space heating, cooling, and lighting technologies, (2008). https://dspace.library.uu.nl/handle/1874/32937 (accessed November 8, 2022).

[75] J. Young, F. Mcilwaine, B. Smit, S. Garcia, M. van der Spek, Process-informed adsorbent design for direct air capture, Chemistry, 2022. https://doi.org/10.26434/chemrxiv-2022-gn7r2.

[76] Frequently asked questions about direct air capture and CO_2 removal, (n.d.). https://climeworks.com/faq-about-direct-air-capture (accessed November 4, 2022).

[77] K. Lebling, H. Leslie-Bole, Z. Byrum, L. Bridgwater, 6 Things to Know About Direct Air Capture, (2022). https://www.wri.org/insights/direct-air-capture-resource-considerations-and-costs-carbon-removal (accessed November 4, 2022).

[78] H. Griffin, Pale Blue Dot Energy and CE partner to deploy Direct Air Capture in UK, Carbon Eng. (2020). https://carbonengineering.com/news-updates/pale-blue-dot-energy-and-carbon-engineering-partnership/ (accessed November 6, 2022).

[79] H. Griffin, Engineering of world's largest Direct Air Capture plant begins, Carbon Eng. (2019). https://carbonengineering.com/news-updates/worlds-largest-direct-air-capture-and-sequestration-plant/ (accessed November 6, 2022).

[80] D. Sandalow, J. Friedman, C. McCormick, S. McCoy, Direct Air Capture of Carbon Dioxide Innovation for Cool Earth Forum (ICEF), 2018. https://www.globalccsinstitute.com/wp-content/uploads/2020/06/JF_ICEF_DAC_Roadmap-20181207-1.pdf.

[81] R. Chauvy, L. Dubois, Life cycle and techno-economic assessments of direct air capture processes: An integrated review, Int. J. Energy Res. 46 (2022) 10320–10344. https://doi.org/10.1002/er.7884.

[82] M. Ozkan, S.P. Nayak, A.D. Ruiz, W. Jiang, Current status and pillars of direct air capture technologies, IScience. 25 (2022) 103990. https://doi.org/10.1016/j.isci.2022.103990.

[83] U.C.C.C. (UNEP-C. UNEP, Emissions Gap Report 2020, 2020. https://www.unep.org/emissions-gap-report-2020.

[84] Orca is Climeworks' new large-scale carbon dioxide removal plant, (n.d.). https://climeworks.com/roadmap/orca (accessed November 4, 2022).

[85] Mammoth: our newest direct air capture and storage facility, (n.d.). https://climeworks.com/roadmap/mammoth (accessed November 4, 2022).

[86] J. L, OXY & Carbon Engineering to Build the World's Largest Carbon Capture Plant, Carbon Credits. (2022). https://carboncredits.com/occidental-starts-building-worlds-largest-carbon-capture-plant/ (accessed November 4, 2022).

[87] H. Griffin, Direct Air Capture Global Deployment Approach, Carbon Eng. (2022). https://carbonengineering.com/news-updates/deployment-approach/ (accessed November 4, 2022).

[88] ExxonMobil expands agreement with Global Themostat sees promise in direct air technology, ExxonMobil. (n.d.). https://corporate.exxonmobil.com:443/news/newsroom/news-releases/2020/0921_exxonmobil-expands-agreement-with-global-thermostat-re-direct-air-capture-technology (accessed November 4, 2022).

[89] Global Thermostat Renews Agreement with ExxonMobil, PRWeb. (n.d.). https://www.prweb.com/releases/2022/5/prweb18654031.htm (accessed November 4, 2022).

[90] G. Thermostat, Global Thermostat to Supply Equipment Needed to Remove Atmospheric CO2 for HIF's Haru Oni eFuels Pilot Plant, Glob. Thermostat. (2021). https://globalthermostat.com/2021/04/global-thermostat-to-supply-equipment-needed-to-remove-atmospheric-co2-for-hifs-haru-oni-efuels-pilot-plant/ (accessed November 4, 2022).

[91] B.K. Sovacool, C.M. Baum, S. Low, C. Roberts, J. Steinhauser, Climate policy for a net-zero future: ten recommendations for Direct Air Capture, Environ. Res. Lett. 17 (2022) 074014. https://doi.org/10.1088/1748-9326/ac77a4.

[92] Carbon180, Incentivizing DAC deployment with the ESIC Act, Medium. (2021). https://carbon180.medium.com/incentivizing-dac-deployment-with-the-esic-act-d81bd9348f92 (accessed November 8, 2022).

[93] E.Y. Aasen, US House of Representatives pass Inflation Reduction Act, effectively enabling the biggest CCUS market pre-2030 to materialize!, Aker Carbon Capture. (2022). https://akercarboncapture.com/2022/08/ira-passed-enabling-biggest-pre2030-ccus-market/ (accessed November 8, 2022).

[94] DOE Announces $14.5 Million Supporting Direct Air Capture and Storage Coupled to Low Carbon Energy Sources, Energy.Gov. (n.d.). https://www.energy.gov/articles/doe-announces-145-million-supporting-direct-air-capture-and-storage-coupled-low-carbon (accessed November 8, 2022).

[95] N.R. Canada, Energy Innovation Program, Carbon Capture, Utilization and Storage, (2021). https://www.nrcan.gc.ca/science-and-data/funding-partnerships/funding-opportunities/funding-grants-incentives/energy-innovation-program/energy-innovation-program-carbon-capture-utilization-and-storage/energy-innovation (accessed November 8, 2022).

[96] G.A. Canada, Canada's climate finance for developing countries, GAC. (2022). https://www.international.gc.ca/world-monde/funding-financement/climate-developing-countries-climatique-pays-developpement.aspx?lang=eng (accessed November 8, 2022).

[97] J. L, Canada Reveals $2.6B Carbon Capture Tax Credit, The Biggest Climate Item, Carbon Credits. (2022). https://carboncredits.com/canada-carbon-capture-tax-credit/ (accessed November 8, 2022).

[98] UK to award £54M to 15 projects developing innovative carbon removal technology, Green Car Congr. (n.d.). https://www.greencarcongress.com/2022/07/20220710-uk.html (accessed November 8, 2022).

[99] Net Zero Strategy: Build Back Greener - Presented to Parliament pursuant to Section 14 of the Climate Change Act 2008, 2021. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1033990/net-zero-strategy-beis.pdf.

[100] T. Terlouw, K. Treyer, C. Bauer, M. Mazzotti, Life Cycle Assessment of Direct Air Carbon Capture and Storage with Low-Carbon Energy Sources, Environ. Sci. Technol. 55 (2021) 11397–11411. https://doi.org/10.1021/acs.est.1c03263.

[101] G.A. Buchner, A.W. Zimmermann, A.E. Hohgräve, R. Schomäcker, Techno-economic Assessment Framework for the Chemical Industry—Based on Technology Readiness Levels, Ind. Eng. Chem. Res. 57 (2018) 8502–8517. https://doi.org/10.1021/acs.iecr.8b01248.

[102] G.A. Buchner, K.J. Stepputat, A.W. Zimmermann, R. Schomäcker, Specifying Technology Readiness Levels for the Chemical Industry, Ind. Eng. Chem. Res. 58 (2019) 6957–6969. https://doi.org/10.1021/acs.iecr.8b05693.

[103] T. Terlouw, C. Bauer, L. Rosa, M. Mazzotti, Life cycle assessment of carbon dioxide removal technologies: a critical review, Energy Environ. Sci. 14 (2021) 1701–1721. https://doi.org/10.1039/D0EE03757E.

[104] E. Cox, E. Spence, N. Pidgeon, Public perceptions of carbon dioxide removal in the United States and the United Kingdom, Nat. Clim. Change. 10 (2020) 744–749. https://doi.org/10.1038/s41558-020-0823-z.

[105] A. Somoza-Tornos, O.J. Guerra, A.M. Crow, W.A. Smith, B.-M. Hodge, Process modeling, techno-economic assessment, and life cycle assessment of the electrochemical reduction of CO2: a review, IScience. 24 (2021) 102813. https://doi.org/10.1016/j.isci.2021.102813.

[106] A. Hemmatifar, J.S. Kang, N. Ozbek, K. Tan, T.A. Hatton, Electrochemically Mediated Direct CO_2 Capture by a Stackable Bipolar Cell, ChemSusChem. 15 (2022). https://doi.org/10.1002/cssc.202102533.

[107] C.A. UK, The path to net zero, Clim. Assem. UK. (n.d.). https://climateassembly.uk/report/read/ (accessed November 14, 2022).

[108] I.A. Digdaya, I. Sullivan, M. Lin, L. Han, W.-H. Cheng, H.A. Atwater, C. Xiang, A direct coupled electrochemical system for capture and conversion of CO2 from oceanwater, Nat. Commun. 11 (2020) 4412. https://doi.org/10.1038/s41467-020-18232-y.

[109] A.G. Dickson, Introduction to CO2 Chemistry in Sea Water, (2016). www.iaea.org/sites/default/files/18/07/oa-dickson-chemistry-1901015.pdf (accessed October 6, 2022).

[110] L. Yan, J. Bao, Y. Shao, W. Wang, An Electrochemical Hydrogen-Looping System for Low-Cost CO2 Capture from Seawater, ACS Energy Lett. 7 (2022) 1947–1952. https://doi.org/10.1021/acsenergylett.2c00396.

[111] 2021-05 Global Assessment of DACCS.pdf, (n.d.).

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