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# Direct Air Capture: Technology Status, Cost Outlook and Integration Potential with Industrial Sites

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# Direct Air Capture: Technology Status, Cost Outlook and Integration Potential with Industrial Sites

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## KEYWORDS

Direct air capture; DAC technologies; technology status; techno-economic assessment; $CO_2$ removal cost; refinery case study; spatial footprint

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## SUMMARY

For hard-to-abate industrial sectors, direct air capture (DAC) has gained increasing attention as a potential strategy to mitigate residual $CO_2$ emissions. In particular, DAC may play an important role in the fuels sector, as the capture of $CO_2$ from fossil sources is not eligible for e-fuel production beyond 2040 under current EU legislation, whereas DAC-derived $CO_2$ is an eligible option.

Direct Air Capture (DAC) is considered a technically feasible carbon removal option; however, it is characterized by high reported costs, considerable uncertainty, and a lower level of maturity compared to conventional carbon capture technologies. In this context, this study evaluates the potential application of DAC technologies at industrial sites, by providing an overview of available DAC technologies, their claimed cost ranges and their potential cost evolution over time, as well as by assessing their application through an example refinery case study based on a specific DAC technology.

From a technological and market perspective, only a limited number of companies are active in the DAC landscape, with only a few technologies having reached demonstration or early commercial stage. More specifically, sorbent-based systems are the most mature, with operational capacities exceeding 4 $kt_{CO2}/y$ while solvent-based systems are steadily advancing towards large-scale deployment.

With respect to claimed technology costs, current estimates are highly uncertain and vary widely across technologies, limiting the ability to draw robust conclusions on economic feasibility. Moreover, under realistic future projections, cost levels remain well above policy targets. While different DAC technologies (sorbent-based, solvent-based and mineral looping) show significant differences in maturity and first-of-a-kind costs, scientific literature suggests that they may converge to similar cost ranges at scale. Overall, the economics of DAC are largely influenced by CAPEX and energy costs as well as the carbon intensity of energy sources, with fully electrified systems benefiting from access to low-carbon electricity.

The techno-economic analysis focuses on a refinery case study, where post-combustion $CO_2$ capture using amine-based systems is applied across its emission sources. The remaining emissions are addressed using solvent-based DAC, with the aim of achieving net-zero operations. The results indicate that DAC could contribute to the mitigation of residual emissions in industrial systems, but its economic viability is highly sensitive to energy prices, plant scale and integration conditions. Under the assessed scenarios, costs are estimated at around 370 EUR/$t_{CO2}$ removed (excluding transport and storage), largely driven by energy-related operational expenses.

As far as cost projections to 2050 are concerned, DAC costs remain uncertain and strongly dependent on deployment scale and policy context. By 2050, costs are expected to remain high (≈170–1260 EUR/$t_{CO_2}$), with large-scale deployment occurring mainly after 2050 under stringent climate scenarios. Therefore, DAC should be considered a complementary option for addressing hard-to-abate residual emissions, rather than a primary decarbonization pathway, with deployment most favourable in locations offering low-cost, low-carbon energy and access to $CO_2$ storage infrastructure.

Last but not least, DAC location is driven by low-cost and low-carbon energy as well as the intended $CO_2$ application (storage or utilization) and supporting infrastructure. While co-location with industrial sites may be relevant for $CO_2$ utilisation pathways, the large land footprint of current DAC technologies makes large-scale deployment at existing refineries spatially challenging, favouring dedicated DAC hubs with access to low-carbon energy and $CO_2$ transport and storage infrastructure.

# 1. INTRODUCTION

## 1.1. OBJECTIVE AND BACKGROUND

Direct Air Capture (DAC) has emerged as an alternative decarbonization pathway of increasing interest. DAC can be used either for $CO_2$ removal and storage, generating carbon credits, or as a carbon source for the production of low-carbon fuels such as Renewable Fuels of Non-Biological Origin (RFNBOs), produced from captured $CO_2$ and green hydrogen via electrolysis. Under current EU legislation (third revision of the EU Renewable Energy Directive, RED III, and its Delegated Acts), $CO_2$ used for RFNBO production can originate from industrial, biogenic, or atmospheric sources. However, the use of $CO_2$ from industrial (fossil) sources is only permitted until 2040, after which only biogenic and atmospheric $CO_2$ sources, such as DAC, are expected to remain eligible.

The primary objective of this study is to evaluate the potential application of Direct Air Capture (DAC) technologies at industrial sites, using the application in a refinery as a case study. This investigation aims to provide an overview of DAC technologies and associated cost ranges, drawing on available literature. At present, DAC technologies are significantly more expensive than conventional carbon capture options. This study therefore assesses both the current cost levels of DAC and their potential evolution over time.

## 1.2. SCOPE OF WORK

The study assesses the costs and application potential of Direct Air Capture (DAC) at industrial sites. As explained in this report, today, DAC technologies are associated with high-cost levels, limiting their large-scale deployment. While significant cost reductions are anticipated, these projections remain subject to considerable uncertainty. The scope of this report is therefore to review existing DAC technologies, provide a techno-economic assessment based on available data, and evaluate the potential cost evolution of DAC towards 2050, as well as its possible role in refinery decarbonisation.

The work is presented in six sections, in addition to this introduction. First, an overview of DAC providers, technologies and costs is presented, followed by a more detailed description of the two main technology categories of DAC, i.e. sorbent-based and solvent-based. While costs at large-scale plants are expected to be similar, solvent-based is the closest to realizing such scale and the only one for which sufficient process and integration data are available at scale to support a detailed techno-economic assessment. Therefore, it was chosen for studying the techno-economics of a refinery case. Identifying the optimal DAC technology for the refinery application is outside the scope of this work. The spatial footprint of a DAC plant is an important parameter, and it is discussed in the subsequent section. Projections of DAC deployment to 2030 and 2050 follow, before concluding on the applicability of DAC technology for refineries.

# 2. OVERVIEW OF DAC PROVIDERS, TECHNOLOGIES AND COSTS

In this Chapter, an overview of Direct Air Capture Technologies (DAC) is given including its definition, technology categories, the current landscape of technology providers, and indicative costs claimed by DAC developers. Further details on the two main DAC technologies, i.e. sorbent- and solvent-based systems, are given in terms of process principles, advantages and disadvantages.

## 2.1. DAC DEFINITION AND TECHNOLOGY LANDSCAPE

The latest report on DAC from the U.S. Department of Energy (DoE) defines DAC as "(…) a technology that regenerates a capture medium in a closed loop and/or uses a mechanical air contactor to chemically or physically separate carbon dioxide directly from the outdoor or indoor ambient atmosphere without reliance on above-average carbon dioxide concentrations caused by nearby point sources of emissions" [1]. This means that companies using technologies that do not comply with this definition, are not included in DoE's company overview. For example, Enhanced Rock Weathering (ERW), which is a climate mitigation technology which captures atmospheric $CO_2$ by spreading crushed silicate rocks on land, chemically binding $CO_2$ during natural weathering, is not accounted for because there is no regeneration of the capture medium in a closed loop or use of air contactors.

In EU legislation, DAC is not defined through an explicit, technology-based definition; instead, it is implicitly characterized via its inclusion as 'direct air capture with carbon storage (DACCS)' under the Carbon Removal and Carbon Farming Certification Framework (CRCF) [2]. Here, it is understood as an engineered approach that captures $CO_2$ directly from the atmosphere and delivers permanent carbon removal when combined with long-term storage (DACCS) [3]. It is noted that ERW in EU is also considered as a different carbon removal pathway, not as DAC [4].

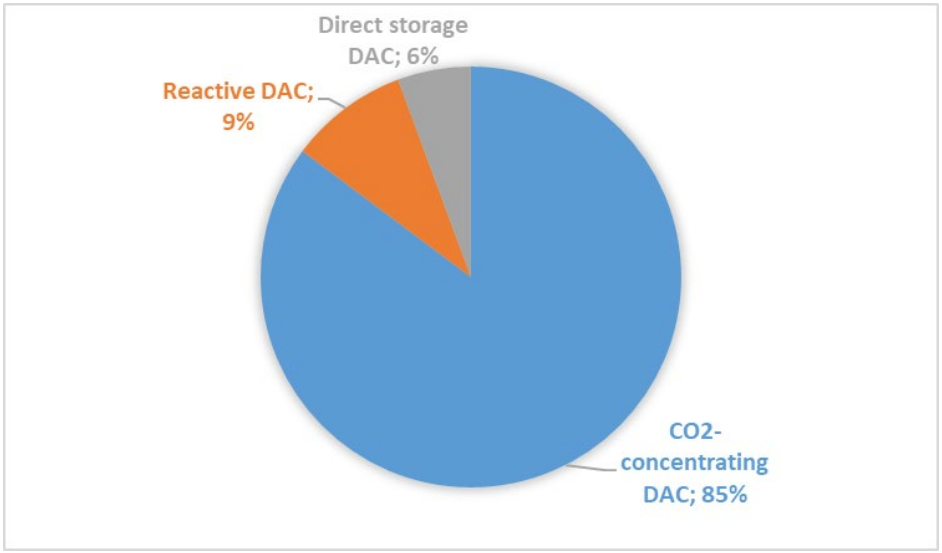
Following the DoE definition, as per January 2025, there are 142 companies active in the Direct Air Capture globally. This number excludes non-profit, research entities and testing centers as well as investing, project developer and carbon credit reseller companies. More than half of these companies, specifically 52% of the total number of companies, are located in the USA [1]. According to the International Energy Agency (IEA), this strong concentration of DAC companies in the United States can be largely attributed to the presence of a strong and deployment-focused DAC framework, including tax credits, the USD 3.5 billion Regional DAC Hubs program and federal carbon dioxide removal (CDR) advance purchase programs which help create early demand by committing public funds to the purchase of verified removals [5].

DAC technologies can be classified into three different categories: $CO_2$-concentrating DAC, Reactive DAC and Direct Storage DAC. The category of $CO_2$-concentrating DAC technologies dominates as shown in Figure 1, accounting for approximately 85% of the total number of companies in the DAC landscape.

### $CO_2$-Concentrating DAC Technologies

$CO_2$-concentrating DAC technologies are designed to separate carbon dioxide from ambient air, producing a more concentrated stream of $CO_2$. This stream may afterwards be utilized, converted, or stored. These methods represent the most dominant and clear-cut approach to direct air capture. The most mature technologies, which are sorbent-based and solvent-based DAC, belong to this category.

*Figure 1* Global share of $CO_2$-concentrating DAC, Reactive DAC and Direct Storage DAC categories, elaborated based on data from [1].




### Reactive DAC Technologies

Reactive DAC encompasses processes that separate carbon dioxide from air and convert it into a valuable product within a single, integrated step, using a regenerable capture medium. During regeneration, the medium transforms the captured $CO_2$ into different chemical products such as methane, methanol, or carbon monoxide. For example, during electrochemical regeneration and conversion, $CO_2$ may be captured by KOH (forming a carbonate-bicarbonate solution) and reduced to e.g. CO. Processes that utilize regenerable capture media to produce carbonate products are also included. Reactive DAC systems often require additional inputs during the single integrated capture/conversion process, for example hydrogen, and are therefore closely linked to the availability of low-carbon energy carriers.

### Direct Storage DAC Technologies

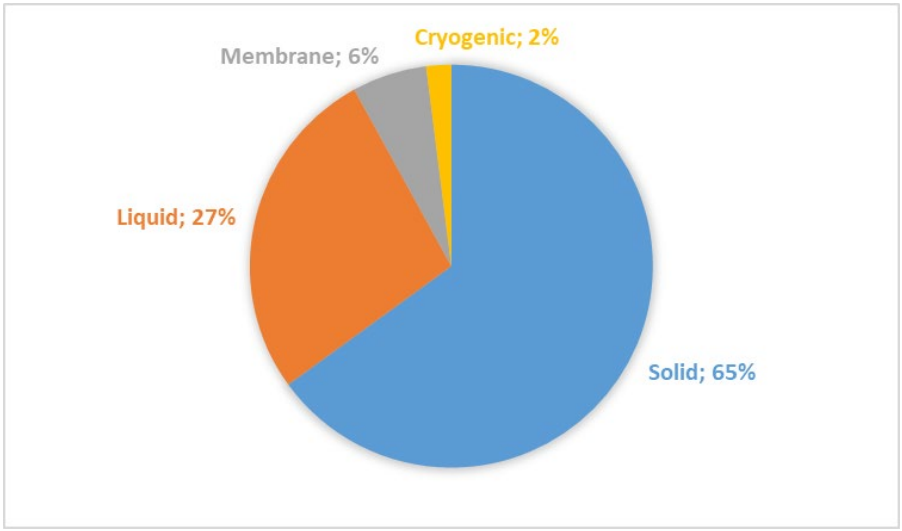
Direct storage DAC technologies include a range of processes that utilize mechanical air contactors and chemical capture media selective to carbon dioxide. Unlike the other DAC technologies, they do not directly regenerate their capture media. Instead, these processes focus on the production of carbonates or other long-lasting compounds derived from the captured $CO_2$ which can either be marketed as valuable materials and sold or disposed of for long-term storage of the captured carbon dioxide.

A potential overlap exists between direct storage DAC and reactive DAC technologies, particularly when valuable products are produced. However, a key distinction is that direct storage DAC does not utilize regenerable capture media. As a result, these systems generally require a continuous supply of additional inputs that enable the capture process, for example, using saline brines or industrial wastewater as a continuous feedstock to mineralize captured $CO_2$ into solid carbonates.

## Overview of Capture Technologies

Three capture medium types exist, applicable for $CO_2$-concentrating DAC and Reactive DAC: solid (sorbent-based), liquid (solvent-based) and membrane-based. Sorbent-based processes deploying metal oxides (CaO, MgO) converted to carbonates through $CO_2$ uptake and regenerated via high-temperature decomposition, are also referred to as mineral looping. According to the DoE company overview, and as shown in Figure 2, the majority of the companies deploying $CO_2$-concentrating technologies (65%) uses a solid capture medium, followed by 27% using a liquid capture medium, and 6% using membrane technology. There are also DAC technologies deploying cryogenics for the separation of $CO_2$ (no capture medium). Membrane-based direct air capture is considered less competitive than sorbent- and solvent-based approaches due to the low concentration and partial pressure of $CO_2$ in ambient air and associated limited efficiency and increased energy demand as well as limitations in $CO_2$ purity; consequently membranes are generally considered as complementary or hybrid components rather than primary DAC technologies [6], [7], [8], [9]. Cryogenic approaches are also generally less competitive, largely due to the same limitation faced by membrane-based processes, the low partial pressure of $CO_2$ in ambient air, which imposes significant thermodynamic and energy penalties on separation [6], [10]. The regeneration of the capture medium differs from technology to technology and is typically assisted by temperature, vacuum, moisture or a combination of them. Regeneration can also be chemical or electrochemical, with many companies mentioning their intention to use electrochemical regeneration. Electrochemical regeneration is described in several technologies under both $CO_2$-Concentrating and Reactive DAC Technologies categories.

***Figure 2*** Types and share of capture media used by DAC companies, elaborated based on data from [1]. Cryogenics uses no capture media.



## 2.2. IDENTIFICATION OF KEY DAC PROVIDERS AND CLAIMED COSTS

### 2.2.1. DAC providers

With an eye on DAC technologies that are most readily available, reached or expected to reach pilot or demonstration stage in the near future, two main identification criteria are set: technology maturity and deployment status. Based on these criteria, a number of DAC providers is identified as particularly relevant in the context of the present study. These include Climeworks, Carbon Engineering, Global Thermostat, Heirloom Carbon Technologies, and Skytree. These companies represent a range of technological approaches and development stages, from pilot-scale demonstrations to commercial operation. Table 1 compares the companies by capture medium, development stage, plant scale and industrial technology readiness level (TRL). The latter uses DoE's TRL definition [11], as also reported in [6]. Overall, the table highlights that there is variation in technology capture medium, scale and technology maturity, with only Climeworks having demonstrated multi-kt/y operation to date.

***Table 1*** Shortlist of DAC providers by technology maturity and scale.

| Company | Country | Capture medium | Technology status | Scale | TRL | Source/ Comment |
|---|---|---|---|---|---|---|
| Climeworks | Switzerland | Solid sorbent (amine-based sorbent) | Commercial operation | 36 $kt_{CO2}/y$ (Mammoth plant) - currently ramping-up | TRL 9 | [12], 1st large-scale DAC plant (Orca – 4 $kt_{CO2}/y$) |
| Carbon Engineering | USA | Liquid solvent (aqueous KOH solution) | First commercial scale under construction | 500 $kt_{CO2}/y$ (planned – not in operation yet) | TRL 7-8 (expected to reach TRL9 in 2026) | [13], plant was expected to come into operation end 2025. |
| Global Thermostat (acquired by Zero Carbon System) | USA | Solid sorbent | Pilot plant | 1 $kt_{CO2}/y$ | TRL 6 | [14], [15] |
| Heirloom Carbon | USA | Solid sorbent (calcium oxide sorbent) | Pilot plant, building new facility | 1 $kt_{CO2}/y$, building 17 $kt_{CO2}/y$ facility | TRL 6 | [16] |
| Skytree | The Netherlands | Solid sorbent | Small-scale operation (demonstration) | ~0.4 $kt_{CO2}/y$ (greenhouses application) | TRL 6 | [17], [18] |

Climeworks is the most important DAC player using sorbent-based DAC, having established itself as one of the most commercially advanced companies in the direct air capture sector (TRL 9). They built the world's first commercial plant, Orca, in Iceland, with capacity of 4 $kt_{CO2}/y$. Climeworks also built the 2nd commercial DAC plant, called Mammoth, in Iceland, which is currently in operation and ramping-up, designed to reach capacity of 36 $kt_{CO2}/y$ [12]. By coupling capture with permanent geological storage through its partnership with Carbfix, Climeworks offers a full carbon removal pathway rather than a stand-alone capture technology. This combination of operational facilities and integrated storage makes the company one of the clearest examples of DAC commercialization currently in the market.

Carbon Engineering develops direct air capture through a solvent-based process and focuses on very large centralized deployment [13]. They are currently building the first and only announced megaton-scale DAC plant in Texas, USA, under their flagship Stratos project. The company's strength lies in the scale of its under-construction DAC plant. Their technology is currently assessed at TRL 7-8, expected to reach TRL 9 once the Stratos plant is in operation. The plant was expected to come online by the end of 2025, however, as per June 2026, the plant operation is delayed due to component issues [19].

The technology of the rest of DAC providers of Table 1 is placed at TRL 6. Global Thermostat uses a sorbent-based capture system and was acquired by Zero Carbon Systems in 2024. A pilot unit with a nominal capacity of 1 $kt_{CO2}$/y has been operated successfully for several months in Colorado, USA in 2022. The company has linked its technology to algae-related use in Hawaii, showing that captured carbon dioxide can be integrated into specific commercial or industrial applications [14]. Heirloom uses calcium oxide sorbent and stores captured $CO_2$ through mineralization in concrete, giving to the company a clear route from capture to permanent removal. It operates a 1 $kt_{CO2}$/y plant in Tracy, California, while building a new 17 $kt_{CO2}$/y facility with a longer-term target of 320 $kt_{CO2}$/y over the coming decade. Skytree draws on technology connected to the European Space Agency and air scrubbing systems developed for the International Space Station. That heritage gives the company a distinct technical foundation and sets it apart from developers focused primarily on large-scale centralized removal infrastructure. Skytree's main application is small (0.4 $kt_{CO2}$/y scale) applied to greenhouses and vertical farms.

### 2.2.2. Claimed and projected technology costs

In this sub-section, the claimed and projected DAC costs by the developers are discussed. Throughout the report, costs are given in EUR/$t_{CO2}$. When costs were reported originally in USD, they are converted to EUR by multiplying with a factor of 0.84.

Reported costs for direct air capture vary widely across providers and technologies, with values ranging from approximately 50 EUR/$t_{CO2}$ to over 1000 EUR/$t_{CO2}$. This broad range reflects differences in technology maturity, scale of operation as well as energy sources, while it is noted that validation of claimed costs is not possible due to limited/unavailable publicly technical information of each technology. A critical distinction must be made between costs reported per ton of $CO_2$ captured and costs reported per ton of net $CO_2$ removed. Costs reported per ton of $CO_2$ captured (gross costs) do not account for emissions associated with operating the DAC process. Net $CO_2$ removal costs (net costs) account for the above within a defined system boundary and are therefore more appropriate for climate impact assessment. The boundary conditions applied to reported net removal costs may vary between studies and should therefore be considered when comparing claimed costs across technologies or providers, particularly when assessing future cost reduction potential. For example, the claim of the very low cost of 50 EUR/$t_{CO2}$ refers to solely costs of the capture process in a best-case OPEX-driven scenario with electricity price as low as 0.02 EUR/kWh [20].

Table 2 presents indicative reported costs from various DAC providers. The table details the respective companies, claimed costs together with their calculation basis (gross or net), and offers supplementary comments regarding other relevant information. For correct interpretation of the table, the reader is asked to take into account the calculations basis of the claimed costs, targeted (thus, non-demonstrated) vs. realized costs and assumptions made, such as specific energy prices or presence of policy incentives and funding schemes.

*Table 2* Indicative claimed costs from several DAC providers.

| Provider | Claimed cost (EUR/$tCO_2$) | Comment |
|---|---|---|
| Climeworks | 210-300 EUR/$t_{CO2}$ captured | Climeworks' projected cost for captured $CO_2$ by 2030 [21]. |
| | Target: 336-504 EUR/$t_{CO2}$ net removed | Climeworks' estimated cost for net $CO_2$ removal by 2030 [21]. |
| | Current: 672-1008 EUR/$t_{CO2}$ net removed | Calculated in this work based on current targets; Climeworks mentions "This represents an overall carbon removal cost reduction of up to 50% compared to today's costs in Generation 2". |
| Carbon Engineering | 77-200 EUR/$t_{CO2}$ captured | Based on Keith et al. [22]; Includes $CO_2$ compression but excludes transport and storage. |
| Global Thermostat | Target: < 42 EUR/$t_{CO2}$ | Target; Global Thermostat mentions "at a climate relevant scale", assuming learning-by-doing cost reductions. [23] |
| Heirloom | Target: < 84 EUR/$t_{CO2}$ net removed | Target by 2035; Assumes subsidies and U.S. tax credits; intended sales price. [24] |
| Skytree | - | No publicly disclosed cost figures available. |

US Department of Energy (DoE) has set a carbon dioxide removal (CDR) target cost of 100 USD/$t_{CO2}$ (84 EUR/$t_{CO2}$) by 2050 [25], where CDR is defined as "wide array of approaches that capture $CO_2$ directly from the atmosphere", thus including DAC. Several companies have reported costs at that range (Heirloom, Carbyon [20], Holocene [26]). At the same time, latest DAC review publications agree that this target is not realistic, and point at a cost range of 200-500 EUR/$t_{CO2}$ at cumulative deployment of 1 $Gt_{CO2}$/y instead [6], [27].

Sievert et al. [27] uses a structured and evidence-based approach to project long-term DAC costs. A novel methodology is used to account for how each technology component improves with cumulative deployment. Rather than applying generic learning curves derived from other emerging energy technologies, they estimate experience rates, defined as the percentage reduction in unit cost achieved with each doubling of cumulative installed capacity. This methodology links these experience rates with technology-inherent characteristics, rather than relying on generic learning curves derived from other emerging technologies such as solar photovoltaics. The difference with previously emerging technologies, like photovoltaics, is that DAC uses mostly non-novel equipment, such as blowers, heat exchangers, compressors, which exhibit limited learning and have low experience rates. Therefore, cost reductions are fundamentally constrained by the low learning rates of the non-novel industrial components, which account for the majority of capital and operational expenditures.

By evaluating design complexity and customization requirements of DAC components through expert interviews and applied multi-component experience curves, Sievert et al. [27] derived cost projections for three DAC technologies: solvent-based, sorbent-based, and CaO ambient weathering at 1 $Gt_{CO2}$/y cumulative deployment. CaO ambient weathering refers here to a process in which $CO_2$ binds to CaO in a carbonation phase in an air contactor structure and regenerates it in a

calcination phase. This process is often also referred to as mineral looping. The authors highlight two key differences when comparing these three technologies: the size of the first commercial plant and the technology TRL of these plants. For the cost estimates for the initial capacity, which is equivalent to the first commercial plant, the Orca plant in Iceland with 4 $kt_{CO2}$/y capacity is considered for sorbent-based DAC, the 1 $kt_{CO2}$/y capacity plant of Heirloom in California is considered for ambient weathering, while for liquid-based DAC, the Stratos plant is considered. The authors consider TRL 7-8 for solid sorbent DAC as it is the most advanced and TRL 4 for liquid solvent DAC, since no plant has yet been commissioned (note that following the DoE's TRL definition [11], the solvent-based technology is assigned to TRL 7-8 in Table 1 of this work). The results for the initial capacities plants, similar to First-of-a-kind (FOAK), and projected costs at 1 $Gt_{CO2}$/y cumulative deployment, similar to Nth-of-a-kind (NOAK) are shown in Table 3. For all three technologies, identical transport and storage pathways have been considered.

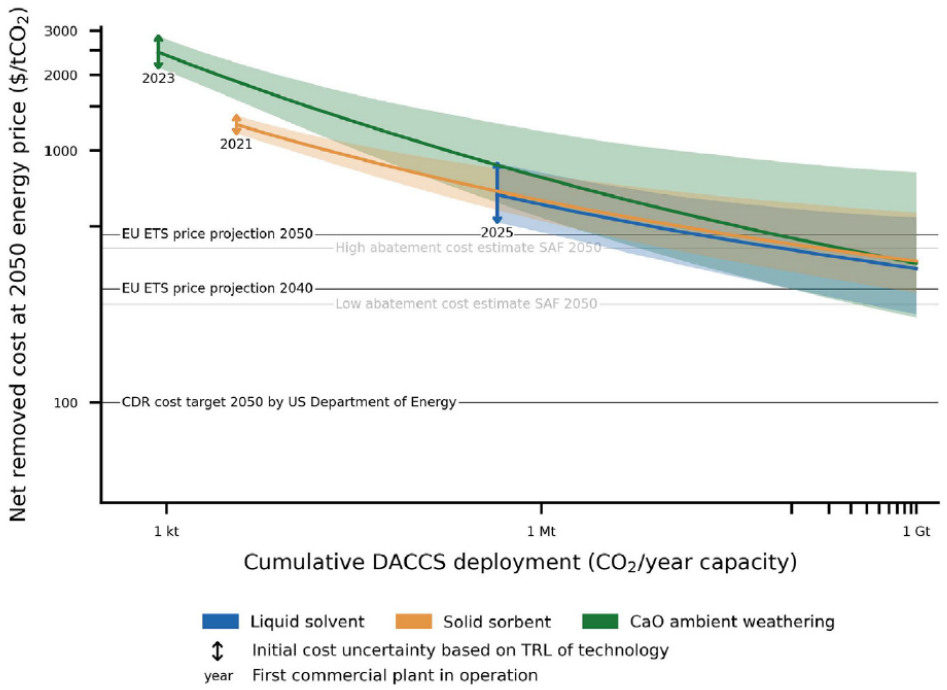
***Table 3*** Current (median) DAC cost calculations and cost projections at 1 $Gt_{CO2}$/y cumulative deployment [27]. Values originally provided in USD, converted to EUR by using a factor of 0.84.

| DAC technologies[1] | Cost estimates for initial capacity (EUR/$t_{CO2}$ net removal) | Projected costs at 1 Gt/y cumulative deployment (EUR/$t_{CO2}$ net removal) |
|---|---|---|
| Liquid solvent | 563 | 286 |
| Solid sorbent | 1077 | 314 |
| CaO ambient weathering | 2084 | 312 |

[1] Transport and storage pathways are identical for the three technologies analysed

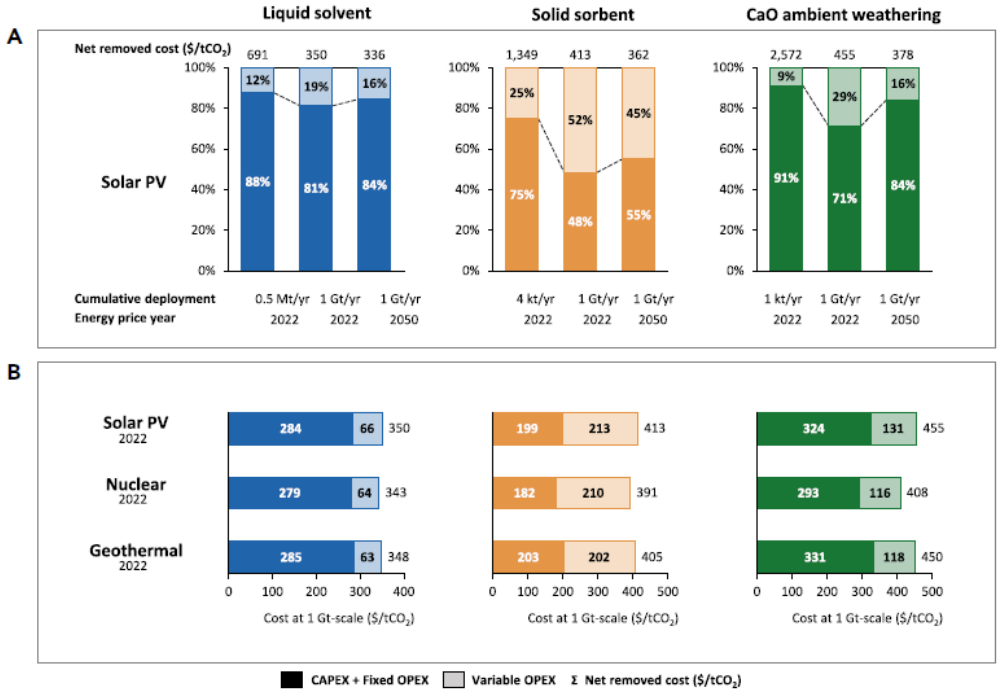
The cost estimates for the initial capacity vary significantly between technologies, which reflects different technology readiness levels (solid sorbent has TRL=9, while liquid solvent TRL=7-8). However, cost projections at 1 $Gt_{CO2}$/y cumulative deployment are very similar for the three different technologies at around 300 EUR/$t_{CO2}$ net removed. This suggests that none of the technologies assessed can be considered superior to each other, and that given the uncertainty involved, all three DAC technologies should be rapidly deployed to see what cost improvements will be achieved. Furthermore, the projects costs are three times higher than the DoE target. The above is depicted in Figure 3 [27]. The cost trajectory of each technology begins at the initial plant scale and increases to 1 $Gt_{CO2}$/y cumulative design capacity. Thick lines represent the 50$^{th}$ percentile while coloured areas represent the uncertainty range between the 5$^{th}$ and 95$^{th}$ percentiles of cost estimates. Separate lines are used to show the long-term US DoE target of 100 USD/$t_{CO2}$, the projected 2040 and 2050 EU ETS prices, and the abatement cost estimates projected for sustainable aviation fuel in 2050 [28]. It is noted that although current EU ETS prices is at approximately 70-80 EUR/$t_{CO2}$ [29], the figure shows projected 2040 and 2050 EU ETS prices at 237 EUR/$t_{CO2}$ (282 USD/$t_{CO2}$) and 390 EUR/$t_{CO2}$ (464 USD/$t_{CO2}$) [30] (this report does not assess the feasibility of, nor makes projections on, future EU ETS prices).

***Figure 3*** Net removed cost trajectories for liquid solvent DACCS (blue), solid sorbent DACCS (orange), and CaO ambient weathering DACCS (green) at 2050 energy prices, on a log-log scale. Reproduced from Sievert et al., 2024, Joule, under a Creative Commons Attribution (CC BY 4.0) licence [27].




The effect of energy prices and cumulative deployment on DAC costs for both FOAK and NOAK plants is also studied. At large-scale deployment, both CAPEX and fixed OPEX are reduced through experience effects, at a lesser degree in solvent-based DAC compared to the other two. As a result, the share of variable OPEX, which depends on energy sources and their associated emissions, increases. Main cost reductions are seen in future low-carbon energy scenarios, such as those based on solar, nuclear and geothermal energy, with systems that can be electrified benefiting the most. Comparing the two effects, scaling up at 1 $Gt_{CO2}$/y cumulative has a larger effect on costs than transitioning from 2022 to 2050 energy prices. These effects are illustrated in Figure 4, taken from [27].

*Figure 4* Net removed costs for liquid solvent, solid sorbent and CaO weathering DAC technologies and energy sources. (A) Cost comparison, using tracking solar PV and storage (battery for 12 h), as well as natural gas as energy sources. The bars represent cost of $CO_2$ net removed, distinguishing between CAPEX + fixed OPEX and OPEX. The bars differentiate costs across increasing cumulative capacity and between energy cost projections for 2022 and 2050. (B) Absolute net removed cost in USD/$t_{CO2}$ for these technologies at 1 $Gt_{CO2}$/y cumulative design capacity and different electricity inputs at 2022 prices. Reproduced from Sievert et al., 2024, Joule, under a Creative Commons Attribution (CC BY 4.0) licence [27].

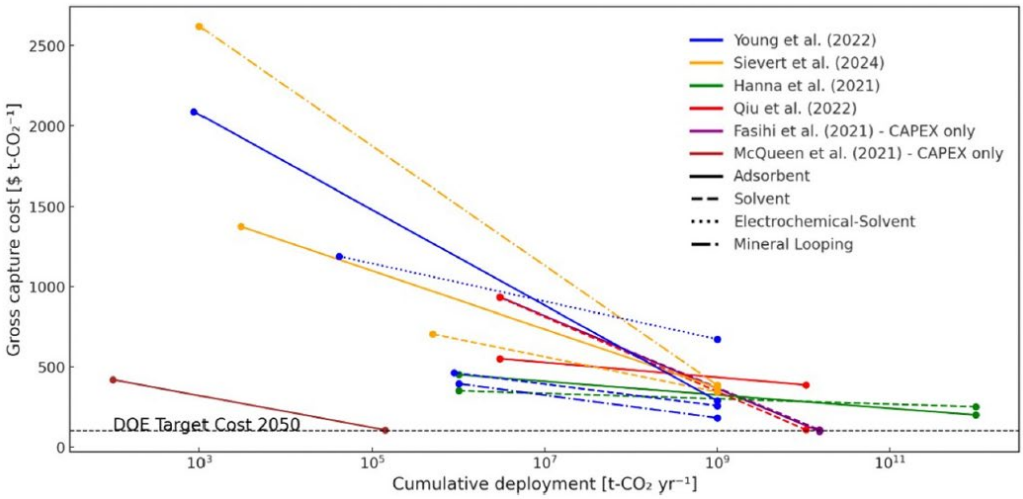



The afore-mentioned cost reductions are less pronounced for solvent-based DAC when the process relies on both electricity and natural gas for the natural gas-fuelled calciners, because the assumed natural gas price increase counterbalances the reduced electricity cost. However, it needs to be noted that the use of electric calciners has been proposed in the literature. While electric calciners are currently available only at small scales, lower than the level required for full-scale solvent-based DAC, they offer a promising potential for decoupling solvent-based technology from natural gas reliance, unlocking further cost reductions if scaled up effectively in the future [31].

Spek et al. [6] conducted a massive review of more than 800 publications on DACCS, including the publication of Sievert et al. [27] discussed above. They discuss various aspects of DACCS, such as technology, state of development, techno-economics, environmental performance, policy, equity & justice, public perceptions, monitoring, including also DAC cost. The authors developed Figure 5, showing the 2024 levelized cost of (gross) $CO_2$ captured (LCCC) for FOAK and NOAK plants using different learning rates available in literature. Most studies project DAC cost between 170 and 400 EUR/$t_{CO2}$ at 1 $Gt_{CO2}$/y cumulative deployment. Again, even at that scale, cost projections do not align with the cost target for 2050, except for

two cases of solid sorbent technology and one case for solvent technology. This points towards unrealistic targets set by DoE, with the authors suggesting its revision.

***Figure 5*** Published cost trajectories for four DAC technologies, i.e. Adsorbent, Solvent, Electrochemical-solvent and Mineral looping. Reproduced from Ref. [6] with permission from the Royal Society of Chemistry. The authors have harmonized the cost calculations from the various reference sources to 2024 LCCC (levelized cost of (gross) $CO_2$ captured). Dotted line depicts DoE target of 100 USD/$t_{CO2}$ by 2050.



# 3. TECHNOLOGY DESCRIPTION

This chapter provides a more detailed discussion of the most relevant DAC technology categories, namely solvent-based and sorbent-based systems. While a wide range of DAC concepts is currently under development, many of which are at the experimental or pilot scale, the most technologically advanced representative of each category is selected to illustrate the underlying process principles. Specifically, Climeworks is used as the reference case for sorbent-based DAC, and Carbon Engineering for solvent-based DAC, due to their relative maturity and scale of deployment.

## 3.1. SORBENT-BASED DAC TECHNOLOGY

Sorbent-based Direct Air Capture is the dominating DAC technology in terms of active companies, and from the aspect that it is still the only one having reached TRL9. For this report, the sorbent-based technology developed by Climeworks is discussed, due to its deployment scale. The technology is based on an adsorption-desorption cycle, where air is directed via large fans towards an adsorbent material, which captures $CO_2$ from the air.

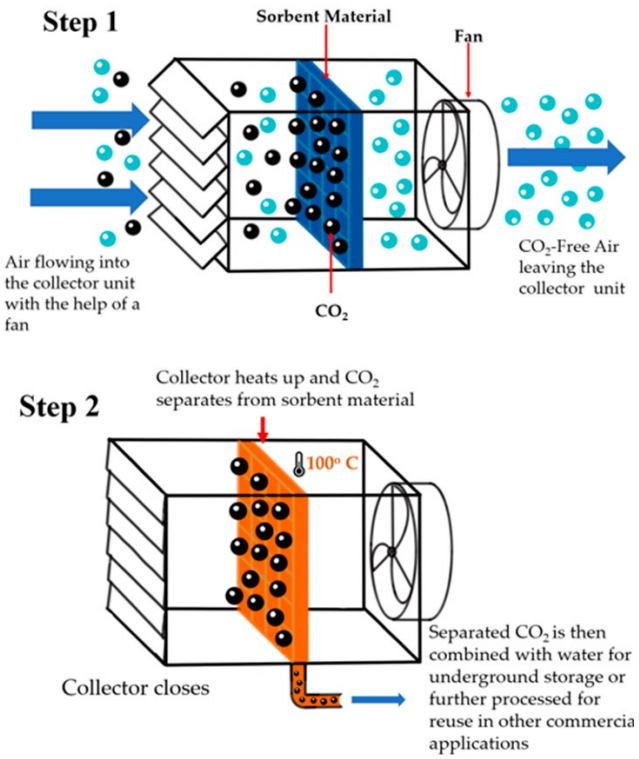
The main parts of the process listed below and illustrated in Figure 6 [12]:

- Capture/adsorption: Ambient air is collected by large fans, and a filter material captures $CO_2$ from the air.
- Desorption: Once the filter is saturated, high temperature 80-100°C and/or vacuum are used to regenerate the sorbent.
- $CO_2$ conditioning: $CO_2$ is cooled down to separate water leading to a high-purity $CO_2$ stream, which is then compressed for storage or use.

Favourable features of sorbent-based DAC are its modularity and scalability, given that the adsorbers are in standard 40 ft containers that can be stacked on top of each other (like in Mammoth project [12]). In addition, its operation under low-temperature regeneration at 80-100°C means that low-grade heat can be used, such as geothermal energy. It is previously mentioned that such technology is being demonstrated at a 36 $kt_{CO2}$/y scale DAC facility in Iceland by Climeworks, which will allow to reduce technology performance uncertainty, and close engineering gaps, enabling near-term deployment of scaled-up sorbent-based DAC systems.

Drawbacks of the process are its high energy intensity, driven by the fans, vacuum generation during desorption and $CO_2$ compression. In addition, sorbents can suffer from loss of capacity over time, might be sensitive to contaminants and, for amine-functionalized sorbents, can exhibit thermal and oxidative degradation, leading to significant sorbent replacement costs [6]. This highlights the need for long-term operation and demonstration at scale, including validation of stable capture performance, emissions monitoring and control, and consistent $CO_2$ product quality over extended operating periods.

*Figure 6* $CO_2$ adsorption-desorption cycle. Reproduced from Garza et al., 2023, energies, under a Creative Commons Attribution (CC BY 4.0) licence [32].



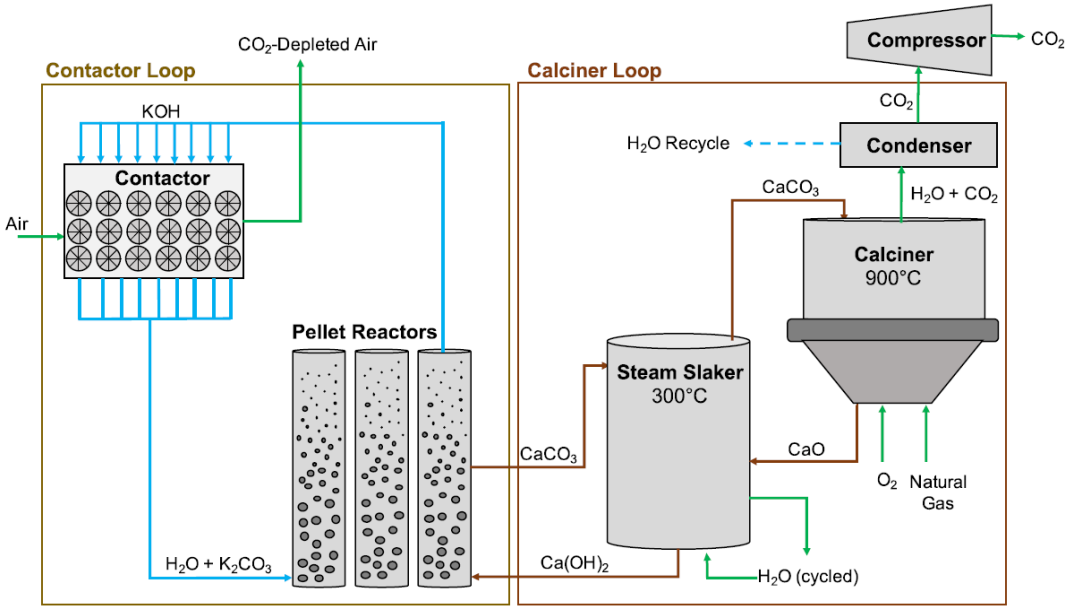

## 3.2. SOLVENT-BASED DAC TECHNOLOGY

Solvent-based direct air capture (DAC) is currently represented at large scale primarily by Carbon Engineering, which applies a liquid absorption process for removing $CO_2$ directly from ambient air. Carbon Engineering is constructing the first announced megaton-scale DAC facility in Texas, USA, in partnership with 1PointFive, a subsidiary of Occidental Petroleum. The partnership covers plant construction, operation, and $CO_2$ sequestration.

The main unit operations of the solvent-based DAC process, as described in literature [22], are:

- Air Contactor: Ambient air is brought into contact with a potassium hydroxide (KOH) solution, where $CO_2$ is absorbed and converted to potassium carbonate ($K_2CO_3$).
- Pellet Reactors: Through an anionic exchange reaction between $K_2CO_3$ and calcium hydroxide ($Ca(OH)_2$), calcium carbonate ($CaCO_3$) is formed while the KOH solution is regenerated and recycled.
- Calciner: Operated at high temperature, $CaCO_3$ is thermally decomposed into $CO_2$, $H_2O$ and calcium oxide (CaO).
- Steam Slaker: The CaO is hydrated to $Ca(OH)_2$, which is recycled to the pellet reactor, thereby closing the calcium loop.

*Figure 7* Representative process flow diagram for the solvent process. Green lines represent gaseous flows, blue lines liquid flows and brown lines solid flows. Reproduced from McQueen et al., 2021, Prog. Energy, under a Creative Commons Attribution (CC BY 4.0) licence [33].




The solvent-based DAC concept is designed for large, centralized installations, rather modular deployment, potentially enabling economies of scale. Moreover, it is based on well-established chemical engineering principles reducing technical, operational, and scale-up risks. Disadvantages of the process are the large physical footprint and complex plant layout and high energy demand. Thermal energy is required primarily in the calciner at 800ºC, making the process strongly dependent on heat supply, typically from natural gas.

Water demand is another important parameter in DAC technologies. The net water balance can vary between DAC processes, from net water consumption to net water production. In the first case, water may be consumed through process requirements or evaporation, while in the second case, water can be captured together with $CO_2$ from air, which can subsequently be recovered during regeneration. In fact, Avnos and ZeoDAC companies explicitly mention their intention to collect and further sell purified water [1].

# 4. TECHNO-ECONOMIC CASE STUDY FOR DAC

## 4.1. INTRODUCTION AND SCOPE OF CASE STUDY

A techno-economic assessment is carried out in this report for a newly installed DAC facility located in Europe. This approach allows the effects of plant scale and European energy pricing on the resulting capture costs to be explicitly analysed and disaggregated. The techno-economic analysis focuses exclusively on solvent-based DAC technology, specifically the system developed by Carbon Engineering, as it is currently the only DAC technology for which sufficiently detailed process descriptions and equipment cost data are available in the peer-reviewed literature, enabling a transparent and reproducible cost assessment [22]. It is noted that this technology is selected due to the availability of detailed process information of the technology, and that the objective of the study is not to identify the optimal DAC technology for the application considered, but rather to assess the performance of the selected solvent-based concept under the defined boundary conditions. The Carbon Engineering publication was published by Keith et al. in 2018 and refers to a 1 $Mt_{CO2}$/y DAC plant, covering the associated operating expenditures (OPEX), capital expenditures (CAPEX), scaling effects, and a sensitivity analysis. It also includes the compression of the captured carbon dioxide up to 15 MPa, but not the transportation and storage.

The case study considers the installation of a DAC facility, to account for the remaining emissions of a refinery, upon applying point-source capture with amines at 95% capture rate. This is based on the dedicated post-combustion carbon capture case studies for representative EU refineries developed by Concawe and TNO [34]. DAC is deployed to account for the remaining emissions (5% non-captured $CO_2$ + emissions due to electricity use in the amine-based capture process). Compensating emissions due to the use of the fossil fuels produced by the refinery (scope 3) are out of the scope of this study.

The DAC process is energy intensive with energy required in the form of either heat or electricity in multiple parts of the process, such as in the air contactors, calciner, pellet reactor, slaker, air separation unit (ASU) for $O_2$ supply to the calciner, $CO_2$ absorber and more. The publication evaluates two energy supply scenarios, which are adopted in the case study:

**Scenario 1:** Natural gas supplies both thermal energy and electricity, through on-site natural gas combustion (gas turbine). This configuration requires 8.81 GJ of natural gas per ton $CO_2$ captured from the air, at 1 $Mt_{CO2}$/y scale plant.

**Scenario 2:** Natural gas is used only for the calciner, with electricity supplied from the grid covering the rest of the energy needs. This configuration requires 5.25 GJ of natural gas and 366 kWh of electricity per ton $CO_2$ captured from the air, at 1 $Mt_{CO2}$/y scale plant.

## 4.2. REFERENCE $CO_2$ EMISSIONS AND DAC CAPACITY

Table 4 summarizes the reference emissions and derived DAC capacity of the case study. The reference case includes a refinery mitigating its emissions by applying point-source capture with amines at 95% capture rate, with the capture process using a gas boiler to meet its energy needs. This is why the $CO_2$ amount captured in the amine-based plant is higher than the reference refinery emissions. In order to achieve a net-zero refinery, the $CO_2$ emissions associated with natural gas (NG) combustion, natural gas upstream production and emissions associated with the

electricity grid for the DAC process, are accounted for the calculation of the required DAC plant capacity. The remaining emissions after applying point-source capture with amines at 95% capture rate and the additional emissions due to electricity consumption (excluding upstream gas supply emissions and venting from the post-combustion capture $CO_2$ conditioning system) in the capture process account for 218.4 $kt_{CO2}/y$. This amount needs to be removed through DAC in order to achieve net-zero. Accounting for the DAC plant inefficiencies (capture rate of 75%) and emissions related to the usage of NG and electricity for the DAC process itself, the required plant capacity for Scenarios 1 and 2 are approximately 280 $kt_{CO2}/y$.

***Table 4*** Emissions and required DAC capacity for the case study.

| | Units | Scenario 1 | Scenario 2 |
|---|---|---|---|
| Reference refinery emissions (total): | $t_{CO2}/h$ | 243.1 | 243.1 |
| $CO_2$ emissions from NG supply for amine-based capture: | $t_{CO2}/h$ | 48.8 | 48.8 |
| Amount of $CO_2$ captured by point-source amine-based capture (incl. extra emissions during natural gas supply): | $t_{CO2}/h$ | 277.2 | 277.2 |
| Remaining emissions after amine-capture: | $t_{CO2}/h$ | 14.6 | 14.6 |
| Additional emissions due to electricity consumption for amine-based capture: | $t_{CO2}/h$ | 13.1 | 13.1 |
| Remaining + additional emissions: | $t_{CO2}/h$ | 27.7 | 27.7 |
| (Assuming 7884 operating hours per year) | $kt_{CO2}/y$ | 218.4 | 218.4 |
| $CO_2$ emissions from direct NG combustion in DAC | $t_{CO2}/h$ | 0.6 | 0.4 |
| $CO_2$ emissions from NG upstream production in DAC | $t_{CO2}/h$ | 6.3 | 3.7 |
| $CO_2$ emissions from electricity grid in DAC | $t_{CO2}/h$ | 0.0 | 3.7 |
| Required DAC plant capacity, accounting for process inefficiencies and DAC-related additional emissions from NG/electricity | $kt_{CO2}/y$ | 280.9 | 280.7 |

In this work, net $CO_2$ removed refers to the $CO_2$ captured from the atmosphere minus the emissions associated with natural gas and electricity use within the system boundary defined in Equation 1. These are calculated based on the gas input for the turbine and the calciner in Scenario 1 and the additional electricity input in Scenario 2, and taking into account upstream natural gas emissions and emissions from the grid. Emissions and costs associated to transport and storage are not included. Notice that the costs are not using the term "$CO_2$ avoided" in DAC, since we do not avoid $CO_2$ as it is already in the atmosphere, therefore the term per "$CO_2$ removed" is more appropriate, and is used in this report.

*Net $CO_2$ removed by DAC = $CO_2$ captured from the air*
*- non-captured $CO_2$ emissions from direct NG combustion*
*- $CO_2$ emissions from NG upstream production*
*- $CO_2$ emissions from electricity grid (Equation 1)*

To account for natural gas upstream emissions intensity, electricity grid emissions and gas and electricity prices, the values listed in Table 5 are used. For electricity use, an emission factor of 363.8 $g_{CO2eq}/kWh$ is assumed as the base case. This value was provided by one of the refineries participating in the post-combustion carbon

capture case study developed previously by Concawe and TNO [34]. It is therefore intended to represent a refinery-specific electricity supply rather than the average European electricity mix. The assumed value is substantially higher than the reported European average electricity carbon intensity for 2024 of 254 $g_{CO2eq}$/kWh [35]. To assess the influence of electricity emissions intensity on the results, the sensitivity analysis considers a higher-emissions case, the 2024 European average, and a fully decarbonised electricity supply. The resulting effects on the net $CO_2$ removed and the total cost per tonne of $CO_2$ removed are assessed.

***Table 5*** Emission intensity and price values used for electricity and natural gas.

| Parameter | Unit | Value |
|---|---|---|
| Intensity of natural gas upstream | $g_{CO2}$/MJ | 20 |
| Natural gas price | EUR/kWh | 0.058 |
| Electricity grid emissions intensity | $g_{CO2eq}$/kWh | 363.8 |
| Electricity price | EUR/kWh | 0.1159 |

By using equation 1, the net $CO_2$ removed by DAC, accounting for the emissions associated to the DAC process from the use of natural gas and electricity. In Scenario 1, with required DAC plant capacity of 280.9 $kt_{CO2}$/y, 218.4 $kt_{CO2}$/y are net removed, leading to net-zero refinery. Similarly, in Scenario 2, net-zero is achieved with DAC plant of 280.7 $kt_{CO2}$/y capacity. The difference between the amount of carbon dioxide removed from the atmosphere and the actual net amount accounted for considering the natural gas- and electricity grid-associated emissions is significant, and highlights the importance of evaluating the entire system, including energy sources and their emissions, to gain an accurate understanding of net carbon removal.

## 4.3. OPERATIONAL EXPENDITURE (OPEX)

OPEX is split into fixed + non-energy variable OPEX and (energy dependent) variable OPEX. The reference publication by Keith et al. used in this work considers the fixed + non-energy variable OPEX (EUR/$t_{CO2}$) constant, and includes non-fuel operations and maintenance by unit, labour, water and make-up chemicals. They assume process water cost of 0.08 EUR/$m^3$, while there is Ca discharge of 1% in each cycle, serving as a purge for managing the build-up of non-process elements such as dust entering the air contactors. Fixed + non-energy variable OPEX is 35.3 EUR (USD 42) per $t_{CO2}$ captured from the atmosphere.

Variable OPEX is determined by the natural gas and electricity consumption. The results are shown in Table 6. The specific OPEX for Scenario 1 and 2 is 221.4 and 208.0 EUR/$t_{CO2}$ net removed, respectively. In Scenario 2, this cost is slightly lower indicating a small benefit in using both natural gas and electricity over natural gas only (Scenario 1) at the given conditions.

*Table 6* Specific OPEX break-down for Scenarios 1 and 2.

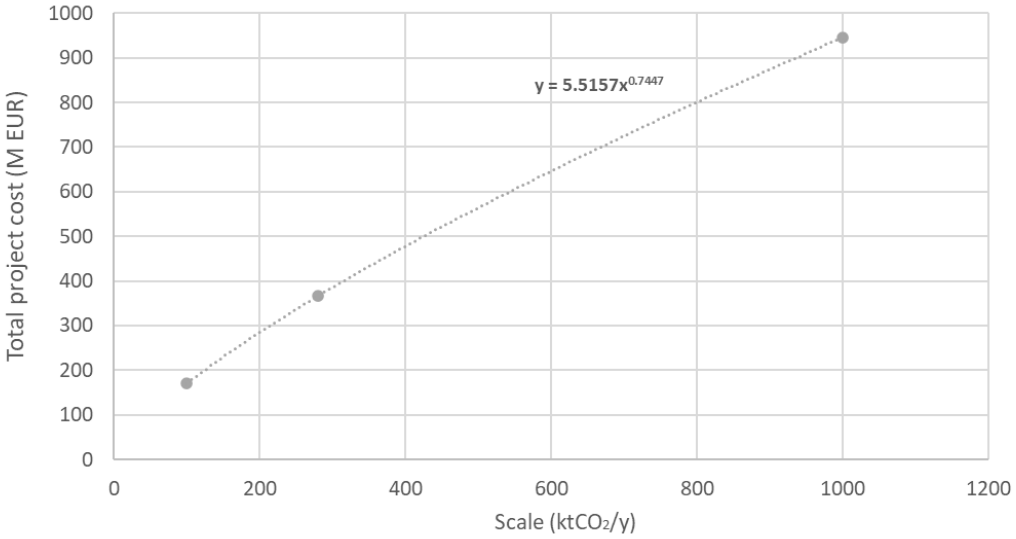
| Parameter | Unit | Scenario 1 | Scenario 2 |
|---|---|---|---|
| Fixed + non-energy variable OPEX | EUR/$t_{CO2}$ from air | 35.3 | 35.3 |
| Variable OPEX (energy) | | | |
| Natural gas input | GJ/$t_{CO2}$ from air | 8.81 | 5.25 |
| | kWh/$t_{CO2}$ from air | 2447 | 1458 |
| Specific natural gas cost | EUR/$t_{CO2}$ from air | 141.8 | 84.5 |
| Electricity input | kWh/$t_{CO2}$ from air | 0.0 | 366 |
| Specific electricity cost | EUR/$t_{CO2}$ from air | 0.0 | 42.4 |
| Specific variable OPEX energy | EUR/$t_{CO2}$ from air | 141.8 | 126.9 |
| Specific OPEX (total) | EUR/$t_{CO2}$ from air | 172.1 | 161.8 |
| | EUR/$t_{CO2}$ net removed | 221.4 | 208.0 |

## 4.4. CAPITAL EXPENDITURE (CAPEX) RESULTS AND SCALING EFFECTS

The plant scale in the publication of Keith et al. from Carbon Engineering [22] considerably differs from this report's case study; namely 1 $Mt_{CO2}$/y scale vs. 280.9 $kt_{CO2}$/y (Scenario 1) and 280.7 $kt_{CO2}$/y (Scenario 2). Since the required DAC plant capacities for Scenarios 1 and 2 are very similar, a capacity of 280 $kt_{CO2}$/y is used as the basis of the subsequent calculations. Estimating CAPEX for a different scale is a very complex exercise because the data available refer to a specific significantly larger scale and the equipment costs are not changing linearly with scale. As a result, the process of adjusting CAPEX estimates to fit this case introduces significant uncertainty, making precise cost calculation difficult.

For example, modular units like the air contactors and pellet reactors scale linearly, while scaling of the calciner-slaker system depends heavily on size. Keith et al. write "…the smallest economically practical size for the complete process is about 100 $kt_{CO2}$/year. At that scale, for the full DAC process, the energy intensity would very close to the 1 $Mt_{CO2}$/year baseline, but the capital cost per unit of capacity would be ~80% larger". Based on this, and the reported value of total project costs of 1126 M$ (945.8 MEUR), the total cost for a 100$kt_{CO2}$/y plant is estimated to be 170.3 MEUR. In Figure 8, a power trendline is chosen, and by interpolation the cost of a 280 $kt_{CO2}$/y plant is found to be 366.5 MEUR. The fact that the cost is found by interpolation between only two points also adds to the uncertainty of the CAPEX estimation approach. A CAPEX sensitivity analysis is conducted in the next section in order to illustrate its potential impact on the total cost of $CO_2$ removed.

***Figure 8*** Total project cost (= CAPEX) as a function of DAC plant scale. By interpolation, the corresponding cost for a 280 $kt_{CO2}/y$ plant is determined.




The cost assumptions used for the calculation of annualized CAPEX in this work are given in Table 7. The annualized CAPEX is calculated by:

$$Annualized\ CAPEX = CAPEX \cdot Annualization\ factor \quad \text{(Equation 2)}$$

$$Annualization\ factor = \frac{r\,(1+r)^n}{(1+r)^n - 1}, \quad \text{(Equation 3)}$$

where $r$: interest rate (decimal form 0.08), $n$: lifetime of the plant (in years).

***Table 7*** Cost assumptions used in this work.

| Parameter | Unit | Value |
|---|---|---|
| Plant lifetime | years | 25 |
| Discount rate | % | 8 |
| Annualization factor | [-] | 0.0937 |
| Annualized CAPEX | MEUR/y | 34.3 |
| Total specific CAPEX | EUR/$t_{CO2}$ net removed | 157.2 |

A comparison between project costs presented in the work of Keith et al. and recently published costs from Stratos plant is worth mentioning. Using the interpolation map in Figure 8, total project cost of a 500 $kt_{CO2}/y$ plant is estimated at 564 MEUR. The total project cost in Stratos project, where a DAC plant of 500 $kt_{CO2}/y$ is developed, is claimed to be 1.2 billion EUR, which is more than double than the estimation in this work based on the work of Keith et al. However, the Stratos project is first-of-a-kind, while this work assumes Nth-of-a-kind, with future NOAK plants benefiting through learnings effects, such as design optimizations and operators' experience etc.

## 4.5. TOTAL COST OF $CO_2$ REMOVAL AND SENSITIVITY ANALYSIS

Combining OPEX and annualized CAPEX yields a total specific cost of 378.6 and 365.2 EUR/$t_{CO2}$ net removed for Scenario 1 and 2, respectively (see Overview in Table 8). For the selected assumptions, OPEX contributes more than CAPEX, covering approximately 60% of the total cost. The effect of specific assumptions to the total cost estimation is further investigated through a sensitivity analysis.

***Table 8*** Overview of OPEX and CAPEX costs for Scenario 1 and 2.

| Parameter | Unit | Scenario 1 | Scenario 2 |
|---|---|---|---|
| Specific OPEX | EUR/$t_{CO2}$ net removed | 221.4 | 208.0 |
| Specific CAPEX | EUR/$t_{CO2}$ net removed | 157.2 | 157.2 |
| Total Cost (OPEX+CAPEX) | EUR/$t_{CO2}$ net removed | 378.6 | 365.2 |

A sensitivity analysis for OPEX is performed on natural gas price, upstream natural gas emission intensity, electricity price and electricity emission intensity and a sensitivity analysis for CAPEX is performed on total project cost and discount rate.

In terms of OPEX, a range of values was developed to capture currently approximate values and potential low or high future trajectories for each variable (noted as Low and High). They are shown in Table 9. Tornado charts in Figure 9 and Figure 10 show the impact of the minimum and maximum values of each parameter. For the electricity grid emissions intensity, an additional intermediate scenario was evaluated and is indicated by a marker on the corresponding bar. It corresponds to a value of 254 $g_{CO2eq}$/kWh, which is representative of the EU average value [35].

For Scenario 1, no results are shown with regards to sensitivity on electricity intensity and price since this scenario uses natural gas to cover the electrical demand of the plant.

***Table 9*** Emission intensity and price ranges used for electricity and natural gas.

| Parameter | Unit | Value | Value low | Value medium | Value high |
|---|---|---|---|---|---|
| Intensity of natural gas upstream | $g_{CO2}$/MJ | 20 | 10 | - | 30 |
| Natural gas price | EUR/kWh | 0.058 | 0.020 | - | 0.100 |
| Electricity grid emissions intensity | $g_{CO2eq}$/kWh | 363.8 | 0.0 | 254 | 400.0 |
| Electricity price | EUR/kWh | 0.1159 | 0.0300 | - | 0.2000 |

For both scenarios, the price of natural gas is the dominant cost driver, yielding cost differences up to 34% in Scenario 1 and to 22% in Scenario 2. In Scenario 1, variations in the intensity of natural gas upstream emissions lead to cost changes of -10 to +12%.

In Scenario 2, beyond the effect of natural gas prices, variations in the electricity price lead to cost changes of ±11%. This is followed by variations in upstream natural gas emission intensity (−6% to +7%) and the emission intensity of the electricity grid (−11% to +1%). The medium value for electricity grid emissions intensity, representative of the EU average, yields cost change of −4%. The afore-mentioned

cost reduction of −11% is a result from the future-idealized case of the target of a fully renewable electricity supply with included negative emissions and a zero-emission grid.

***Figure 9*** Sensitivity analysis results for Scenario 1. Low and high parameter values are shown in Table 9.

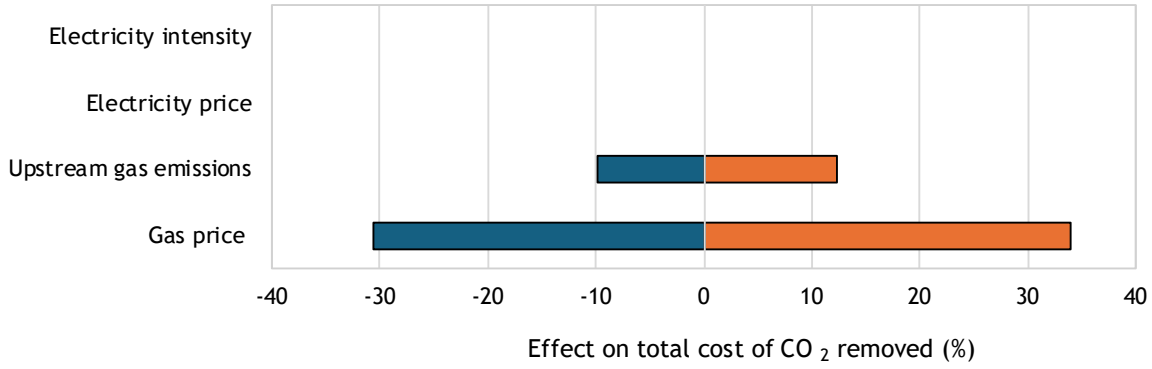
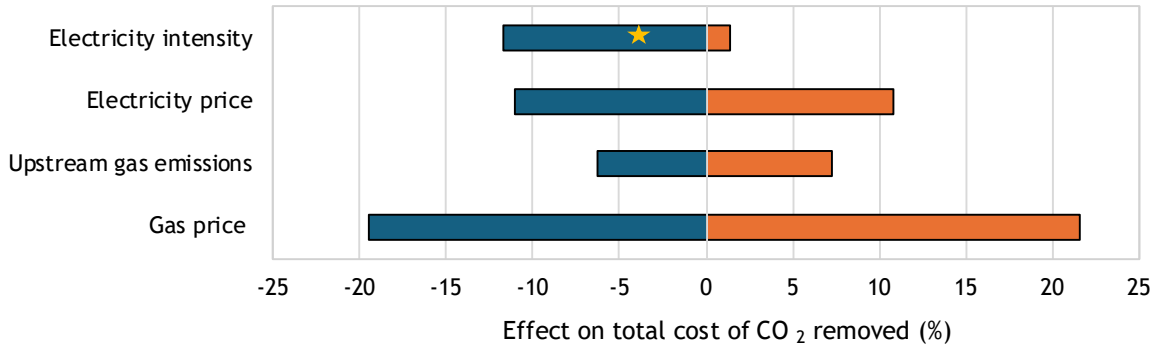



***Figure 10*** Sensitivity analysis results for Scenario 2. Low, medium and high parameter values are shown in Table 9. Effect on total cost of $CO_2$ removed in the medium value assessment is denoted with a star symbol.




The results show that DAC costs are highly dependent on energy prices, carbon intensity of utilities, and plant scale, with costs being approximately 370 EUR per ton of $CO_2$ net removed under the base scenarios assessed, excluding transportation- and storage-related costs. These costs are in line with the publication results, considering the differences in assumptions regarding energy prices and emission intensities.

In terms of CAPEX, the range of values for total project cost and discount rate are shown in Table 10; a ±50% variation on the total project cost of 366.5 MEUR was assumed to study its impact on total cost of $CO_2$ removed. As shown in Figure 11 and Figure 12, a 50% change in the total project cost results is ±21% and ±22% reduction/increase in total costs for Scenario 1 and 2, respectively. Variation in the discount rate lead to change of −4% and 11% for Scenario 1, and −7% to +8% for Scenario 2, indicating lower impact of discount rate than total project cost, for the given value range assumed in this analysis.

*Table 10* Total project cost and discount rate ranges used in the CAPEX analysis.

| Parameter | Unit | Value | Value low | Value high |
|---|---|---|---|---|
| Total project cost | MEUR | 366.5 | 183.1 | 549.4 |
| Discount rate | % | 8 | 6 | 10 |

*Figure 11* Sensitivity analysis results for CAPEX for Scenario 1.

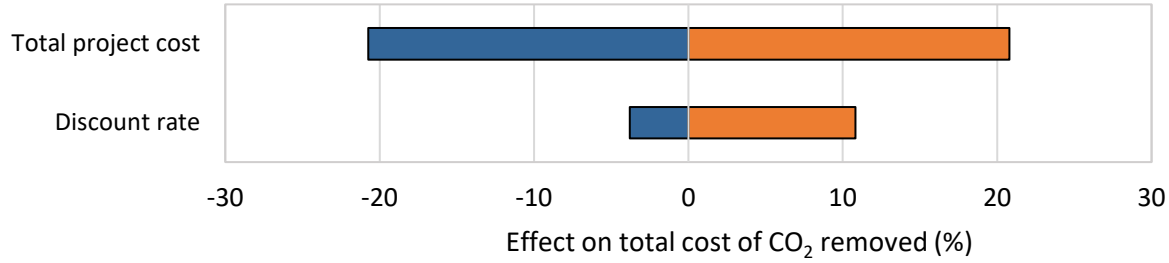
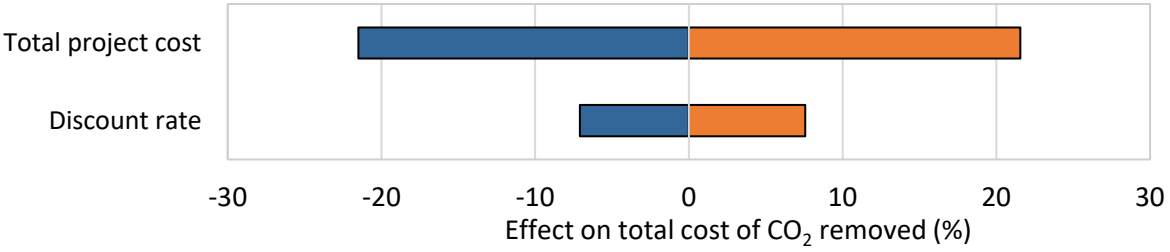



*Figure 12* Sensitivity analysis results for CAPEX for Scenario 2.




## 4.6. DAC SPATIAL FOOTPRINT

DAC can be deployed in different locations, i.e., on-site DAC, off-site DAC, storage-proximate DAC, depending on the intended use of the captured $CO_2$ and the availability of supporting infrastructure. While deployment near low-carbon energy sources and $CO_2$ transport and storage infrastructure may be advantageous, co-location with industrial facilities may be attractive when the captured $CO_2$ is intended for local utilisation, for example in the production of synthetic fuels or chemicals meaning that in cases where $CO_2$ is intended for utilization, the location strategy might shift from optimizing energy and storage access to optimizing integration with the $CO_2$ value chain. The refinery is considered here as a representative case study to assess the spatial implications of DAC deployment at an industrial site.

The area of the refinery in a previous case study by TNO and Concawe for amine-based carbon capture is 337500 $m^2$ [34]. For illustrative purposes, if 5% of this area were available and technically suitable for DAC deployment, this area share corresponds to 16875 $m^2$ or, if we convert it to unit area per amount of $CO_2$ removed per year, to 69.5 $m^2$ per $kt_{CO_2}/y$ of DAC capacity. Actual land availability would depend on site-specific factors, including the presence of sufficiently large contiguous plots, safety distances, existing and planned infrastructure, construction and maintenance access, and utility connections.

Comparison with existing DAC plants shows that current DAC technologies require substantially more area per unit of capacity than that. For example, Carbon Engineering's Stratos plant, currently under-construction, requires more than 500 $m^2$ per $kt_{CO_2}/y$. The footprint of Climeworks' Orca and Mammoth plants is not disclosed, however, by using the "Measure Distance" Tool in Google maps, between 700 and 1000 $m^2$ per $kt_{CO_2}/y$ are estimated to be required. This indicates that a significant amount of area of the refinery would have to be dedicated to DAC, which seems unfeasible as refineries are often already in densely populated industrial sites. Large-scale on-site DAC deployment at existing industrial sites is therefore spatially constrained under current technology designs.

Existing DAC projects are generally being developed at locations with suitable access to low-carbon energy and $CO_2$ storage infrastructure. Consequently, for applications focused on permanent $CO_2$ removal, DAC deployment at dedicated hubs or storage-proximate locations are more attractive than refinery-integrated deployment. Such configurations can also benefit from economies of scale, as DAC facilities can be deployed as large, centralized installations, for example at capacities of around 1 $MtCO_2/y$, rather than as multiple smaller site-specific units.

# 5. COST PROJECTIONS TO 2050 AND IMPLICATIONS

The currently claimed and future costs of direct air capture have been previously discussed in Chapter 2. However, these costs are discussed as a function of cumulative deployment, without providing specific information related to the projected timeline for these cost changes.

To address long-term cost trends and connect projected DAC cost with timeline, Integrated Assessment Models (IAMs) can be utilized. IAMs are forward-looking optimization models that offer a consistent and comprehensive description of the energy system. In the framework of carbon dioxide removal (CDR), they are designed to map out the pathways and necessary transformations required to achieve specified climate targets at the lowest possible cost, constrained by permitted technology choices, policies and a set of assumptions.

Spek et al. [6] discuss cost projections to 2050 (and 2100) of four IAM-based analyses, including their own, with each one including a number of different scenarios. IAMs consistently indicate that direct air capture deployment becomes significant mainly after the middle of the century, with limited deployment expected in the near term. Main drivers for large-scale DAC deployment are stricter climate targets and high carbon emission prices, which encourage DAC as a mitigation strategy when other options may not suffice.

IAM-based projections suggest that by 2050, DAC deployment could range from approximately 23 $Mt_{CO_2}$ removed per year up to 6 $Gt_{CO2}$/y, and by 2100, from 6 $Gt_{CO2}$/y to as high as 20 $Gt_{CO2}$/y. To provide a visual understanding, the above are illustrated in Figure 13 and Figure 14, for 2050 and 2100, respectively. The figures are based on the overview figure of cost trajectories for different DAC technologies by Spek et al., only now highlighted with projected deployments for 2050 and 2100 respectively based on the IAMs results.

A cumulative deployment range of 23 $Mt_{CO_2}$/y to 6 $Gt_{CO2}$/y by 2050 is translated to DAC costs of anywhere between ~170 and ~1260 EUR/$t_{CO2}$ (~200 to ~1500 USD/$t_{CO2}$). It is worth mentioning that no technology pathway, within this literature, reaches the DoE target cost of 100 USD/$t_{CO2}$ by 2050, even under the most optimistic scenario by 2050 with cumulative deployment of 6 $Gt_{CO2}$/y. By 2100, estimates expand further, spanning from 6 $Gt_{CO_2}$/y to as high as 20 $Gt_{CO_2}$/y, implying costs drop to a range of approximately 80-450 EUR/$t_{CO2}$ (~100 to ~500 USD/$t_{CO2}$). Within this literature, two sources project DAC costs of around 100 USD/$t_{CO2}$ [36], [37]; however, one of them considers only CAPEX [37][1]. It is reminded that the costs discussed here consider gross cost of capture (capturing $CO_2$ from ambient air, including CAPEX and OPEX, but excluding emissions from energy or feedstock use, or other life cycle activities) to allow a fair comparison between technologies, since net removed depends heavily on energy sources.

The results reveal considerable variability across model outcomes. The reason is that different IAMs use different cost assumptions, availability of alternative CDR (BECCS, reforestation) and assumptions on energy transition. Therefore, the uncertainty of the result is high: on the one hand, DACCS demand may increase if

[1] The reported results are based on harmonized data from Spek et al., meaning that values from different studies are recalculated and compared using consistent methodological assumptions and system boundaries. The harmonization includes alignment of key parameters such as energy supply assumptions, $CO_2$ accounting conventions, functional units (e.g., per ton $CO_2$ removed), and techno-economic and environmental performance metrics, enabling improved comparability across DACCS studies despite differences in original study designs.

other CDR technologies underperform; on the other hand, DACCS may be slower depending on low-carbon energy availability, political situation, policy support and/or social acceptance barriers.

Overall, these projections indicate that DAC is unlikely to become a large-scale, cost-competitive mitigation option for industries such as refineries before 2050. Instead, DAC is best viewed as a complementary option to address residual emissions that cannot be mitigated through conventional carbon capture, electrification, fuel switching and efficiency improvements.

***Figure 13*** Published cost trajectories for four DAC technologies, i.e. Adsorbent, Solvent, Electrochemical-solvent and Mineral looping, adopted by [6], with highlighted (in blue box) projected cumulative deployment by 2050. The original figure is reproduced with permission from the Royal Society of Chemistry; additional shading and annotations were added in this work. Spek et al. [6] have harmonized the cost calculations from the various reference sources to 2024 LCCC (levelized cost of (gross) $CO_2$ captured).

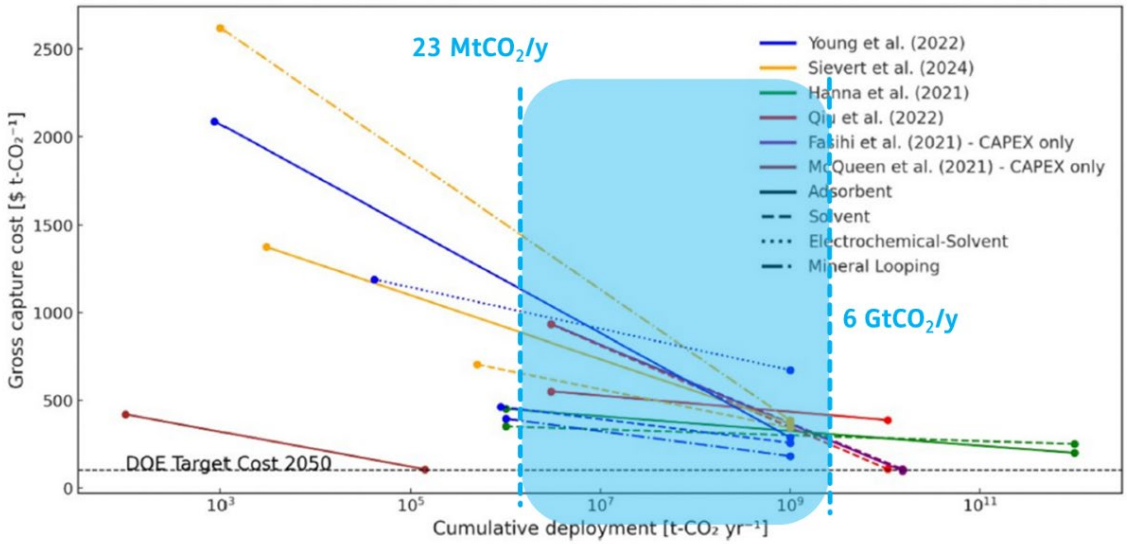
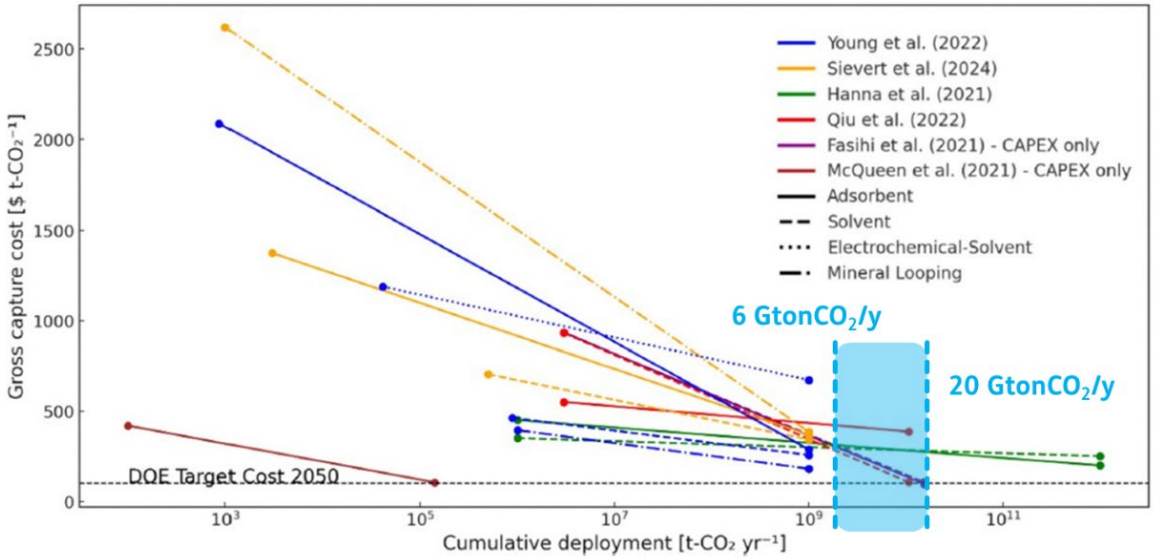


*Figure 14* Published cost trajectories for four DAC technologies, i.e. Adsorbent, Solvent, Electrochemical-solvent and Mineral looping, adopted by [6], with highlighted (in blue box) projected cumulative deployment by 2100. The original figure is reproduced with permission from the Royal Society of Chemistry; additional shading and annotations were added in this work. Spek et al. [6] have harmonized the cost calculations from the various reference sources to 2024 LCCC (levelized cost of (gross) $CO_2$ captured).



# 6. CONCLUSIONS

This work covered the main definitions and state-of-the-art for DAC, main DAC providers and claimed costs of DAC application and projections to 2050. In addition, it presented a techno-economic assessment of a solvent-based DAC case study located in Europe. The main conclusions about the status of DAC and its applicability are summarized below:

- DAC is technically feasible but costly (300-1000 EUR/$t_{CO2}$ net removed); it is significantly more expensive than the DoE cost target for carbon dioxide removal by 2050 of 100 USD/$t_{CO2}$. Even under large cumulative deployment levels, such as 1 $Gt_{CO2}$/y, none of the assessed DAC technologies credibly reaches this target. In addition, cost reductions are limited by low learning rates, since DAC systems are mainly composed of off-the-shelf, non-novel industrial components, such as compressors and fans.
- There is not a single DAC technology that separates itself from the rest, cost-wise. Specifically, solid sorbent, liquid solvent, and mineral looping DAC are projected to have similar cost ranges at gigaton scale (approximately 300 EUR/$t_{CO2}$ median), despite large differences in first-of-a-kind costs and technology readiness levels. Furthermore, the economics of DAC are largely influenced by energy costs and the carbon content of energy sources. Fully electrified systems will benefit the most from low-carbon electricity.
- A techno-economic assessment of solvent-based DAC at a refinery demonstrates that while this technology could enable refinery decarbonization if scalability is possible, it currently costs approximately 370 EUR/$t_{CO2}$ removed (without counting transportation and storage) and is highly sensitive to energy costs, emissions intensity, and plant scale. It is noted that the study does not aim to identify or compare the optimal DAC technology for the application considered, as such an evaluation would require a consistent assessment of multiple technology options based on equally detailed technical and economic data.
- DAC siting is driven by low-cost and low-carbon energy as well as the intended $CO_2$ application (storage or utilization) and supporting infrastructure. While co-location with industrial sites may be relevant for $CO_2$ utilisation pathways, the large land footprint of current DAC technologies makes large-scale deployment at existing refineries spatially challenging, favouring dedicated DAC hubs with access to low-carbon energy and $CO_2$ transport and storage infrastructure.
- Last but not least, based on Integrated Assessment Models reported in the literature, DAC deployment is expected to be limited by 2050, with large-scale rollout occurring mainly after 2050 and only under high-overshoot climate scenarios and high carbon prices.

# 7. GLOSSARY AND ABBREVIATIONS

| | |
|---|---|
| CAPEX | Capital Expenditure |
| CDR | Carbon Dioxide Removal |
| CRCF | Carbon Removal and Carbon Farming Certification Framework |
| $CO_2$ | Carbon dioxide |
| Concawe | Conservation of Clean Air and Water in Europe |
| DAC | Direct Air Capture |
| DACCS | Direct Air Carbon Capture and Storage |
| DoE | U.S. Department of Energy |
| ERW | Enhanced Rock Weathering |
| EU | European Union |
| FOAK | First-of-a-kind |
| IEA | International Energy Agency |
| NOAK | $N^{th}$-of-a-kind |
| OPEX | Operating Expenditure |
| RED III | Renewable Energy Directive III |
| RFNBO | Renewable Fuels of Non-Biological Origin |
| TNO | Netherlands Organisation for Applied Scientific Research |
| **Unit** | |
| $^oC$ | Degree Celsius |
| kWh | Kilowatt-hour |
| $t_{CO2}/h$ | Metric tonnes of carbon dioxide per hour |
| $kt_{CO2}/y$ | Kilotonnes of carbon dioxide per year |

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