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Direct Air capture (DAC) deployment: A review of the industrial deployment

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ABSTRACT

Currently, scientists and investors consider Direct Air Capture (DAC) as one of the candidates to reduce CO_2 emissions. The emissions cut is pressing since 30% of the current greenhouse gas emissions must be addressed by 2030. In seven years, CO_2 removal (CDR) technologies are expected to reach a Technology Readiness Level (TRL), relevant to industrial applications. The most promising technologies are at TRL-7, but the jump to TRL-11 in the new IEA scale for disruptive technologies looks unlikely because the scale-up from small pilots to industrial scale requires time and large investments. Moreover, validation on a large scale is still missing or even unplanned. This work also identifies the critical materials supply chain and the competition with the energy transition as limiting factors which could further hinder DAC deployment and reduce DAC contribution in the next years when a first significant emissions cut should be addressed.

1. Introduction: An ambitious and challenging target

Developing techniques for cutting anthropogenic greenhouse gas (GHG) emissions to near zero is one of the most relevant and demanding targets that the scientific community is facing to combat climate change. To keep global warming to no more than 1.5 °C, as stated in the Paris Agreement, emissions must be reduced by 2030 and reach net zero by 2050 ("The Paris Agreement | UNFCCC," n.d.). The current CO_2 emissions worldwide are around 32 Gt_{CO2}/y and the GHG emissions are progressively growing ("Emissions Gap Report 2022," 2022; "Net Zero by 2050 - A Roadmap for the Global Energy Sector," n.d.). The ambitious plan is to reduce the emissions by 14.4 Gt_{CO2}/y by 2030. The transition requires a rethinking of how society produces and consumes resources, energy, and chemicals. For instance, the energy sector is responsible for around 75% of GHG emissions ("Emissions Gap Report 2022," 2022; "Net Zero by 2050 - A Roadmap for the Global Energy Sector," n.d.). Therefore, technological improvements and innovation should be disruptive enough to catch up with these ambitious environmental goals. The CO_2 removal (CDR) portfolio includes several potential solutions (Hepburn et al., 2019; Terlouw et al., 2021). At the current state, almost all CDR technologies still need dedicated efforts to make them economically appealing and less energy-demanding (IEAGHG, 2021a; Lezaun et al., 2021; Strefler et al., 2018, 2021). Among CDR technologies, direct air carbon capture and sequestration, DACCS or simply DAC, is acquiring more and more interest since it fits the target of net negative emissions (House et al., 2011; IEAGHG, 2021a; Strefler et al., 2018, 2021). This means that the process sequesters and stores more CO_2 than the one produced and released to the environment by the process considering both direct and indirect emissions. Start-ups attract capital and attention despite the costs and the limited commercial markets. These companies received large investments as pointed out in a recent article in the Financial Times (Hook, 2019). Currently, the adsorption, e.g., Climeworks and Global Thermostat (Beuttler et al., 2019; Wurzbacher et al., 2016), and absorption-based, e.g., Carbon Engineering (Holmes and Keith, 2012; Keith et al., 2018), technologies are close to industrial deployment. The present review aims at pointing out that there are potential limitations and brakes to relying on DAC for cutting emissions by 30 % within 2030. Technology Readiness Level (TRL) is one of the main aspects to be considered since the climb from low TRL to higher ladders could be a stiff hurdle to achieve industrial deployment. This aspect has not been investigated yet. To assess the TRL level, we considered IEA's novel TRL scale proposed for CDR technologies (Direct Air Capture 2022 *A key technology for net zero*, 2022). The analysis of the learning rate and learning-by-doing curves, for example, the scale-up from lab scale to industrially relevant plant size, shows that there are some discrepancies between the ideal path and the

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communications/despatches to the public audience and investors from the main DAC engineering companies. We intentionally omit any considerations on the energy analysis and the costs associated with DAC processes because these have been extensively investigated in other reviews and works (Chauvy and Dubois, 2022; House et al., 2011; McQueen et al., 2021; Young et al., 2023, 2022). Instead, we focus on other elements neglected until now to make our assessment unbiased and more exhaustive. This work would contextualize the DAC from the point of view of industrialization and readiness to take part in the GHG emission cut planned in the next 27 years until the net-zero emissions goal is not achieved. We hope that our contribution highlights that DAC is only one of the alternatives in the CDR portfolio. The scientific community should be aware that the time is running out and probably we are in line with planned emissions reduction (Rothenberg, 2023). Thus, the scientific community should also analytically encompass all the available solutions and critically assess their real potential in the process of decarbonization.

2. Overview of DAC technologies' TRL

The assessment of the DAC technologies' TRL is the critical aspect of the present work. The companies active in this field, not surprisingly, protect their in-house technology and know-how without sharing sensible data or relevant pieces of information. This lack of information makes the task complex and full of potential uncertainties associated with our estimates. There are a few peer-reviewed scientific publications from DAC companies, mainly from Carbon Engineering and Climeworks, but these are not sufficient to assess and confirm the TRL because these works mainly discussed the features of the material (adsorbent) or preliminary qualifications of the technology (absorbent). Another source of information is pressing releases, which can refer to the companies' business plans or advertise the planned pilot plants or facilities under construction. From the pilot size only, often measured in yearly capture, it is complex to assign the correct TRL of the proposed technology. Another issue that arose during the scouting process was related to the reliability of such information. Advertisements and digital articles are not peer-reviewed material, and this could lead to the sharing of unchecked information. For this reason, we limited our analysis to companies' websites and trusted trade and technical journals where appropriate. TRL information is crucial to assess technology maturity and state how far it is from its deployment in relevant industrial realities, despite the difficulties in tracking this kind of detail. The scouting activity focused on data freely accessible in scientific databases and information disclosed by the companies themselves as reported in Table 1.

2.1. *Adsorption-based DAC*

Climeworks is one of the most prominent and active engineering-construction-procurement (EPC) companies of the sector. Climeworks has its own adsorption-based DAC technology developed into patented modules. Climeworks has 12 DAC pilot plants in operation, in Switzerland (Hinwi) and Iceland (Orca, 4 kt/y). Mammoth (36 kt/y) is under construction in Iceland. Currently, Climeworks claims a carbon capture cost close to 500–600 USD/t_{CO2}. The company's target is reducing the costs of captured CO_2 by 200 USD/t_{CO2} by 2025 and below 100 USD/t_{CO2} by 2030 thanks to learning-by-doing, scale-up, and larger facilities deployment. Meanwhile, Climeworks aims at increasing the capture volume per facility up to 100 kt_{CO2}/y facilities in the next ten years. The Orca plant operates in collaboration with CarbFix for mineral storage of captured CO_2. This process has been validated in a small pilot in relevant industrial applications, but the integration of a large-scale industrial cluster is still missing as well as the proof of stability. Still, the costs estimate looks reasonable and aligned with the literature.

Global Thermostat is another provider of a solid-based technology based on impregnated honeycomb to lower the pressure drop during the adsorption phase. The company signed several contracts, and the most relevant achievements are the agreements signed with Exxon Mobil and HIF[1] for the commissioning of two DAC pilot plants in 2020, which will contribute to enhancing the scale-up of Global Thermostat capture technology. The agreement has been renewed recently, in April 2022. The DAC plant is designed to capture around 2 kt_{CO2}/y. So, this is a small pilot scale, with only half the capture compared to the Orca site. There is no information on the operation of relevant industrial fields for this plant. They claim that their technology can capture CO_2 with limited costs (around 85–100 USD/t_{CO2}). Conversely to Climeworks, Global Thermostat does not disclose many details on the technology. Thus, it is more challenging to determine a correct TRL level.

GreenCap Solutions is a Norwegian company active in carbon capture from low CO_2 concentration flue gases and it is currently investing resources in its own patented DAC technology. The GreenCap technology relies on the selective adsorption of CO_2 by commercial zeolites, without any chemical pre-treatment, put into modules. This should contribute to cut the investment and maintenance costs. The technology has been tested on a small-scale pilot plant (0.3 kt_{CO2}/y) and modules are already available for commercialisation. GreenCap aims at covering small-scale DAC for CO_2 utilization in agriculture. This target market is different from other DAC companies. There is no specific information on the cost per captured CO_2.

Kawasaki Heavy Industries is currently investing resources in a proprietary DAC solution. The Kawasaki technology exploits CO_2 adsorption over a novel amine-impregnated porous material. There is no published information about the support and the active-amine moieties properties. According to the test they performed on a small lab prototype (5–6 kg_{CO2}/day), the regeneration occurs at 60 °C under vacuum conditions (20 kPa). Kawasaki tested the adsorption process under varying operating conditions, including humidity oscillations, and their experiments claimed to show high stability and resilience of the adsorbent material. The technology is still under development. Kawasaki does not provide any preliminary evaluation of the cost for the capture.

Susteon Inc. is developing its own DAC concept which looks like Climeworks' technology, modules. However, Susteon Inc. is currently the only start-up introducing to the market a combination of DAC and carbon utilization. Conversely to the general concept of DACCS where carbon dioxide is removed from the atmosphere and permanently stored in saline aquifer, mineralized (like in CarbFix technology), use in enhanced oil recovery (EOR), or permanent storage in beneath the seabed, such as in the Northern Lights project, Susteon Inc. proposes an intensified process where the CO_2 recovered from the atmosphere is turned into chemicals, in this case methane, directly inside the same module where CO_2 capture from the air occurs by using a bi-functional material. The bi-functional material is more complex than amine-impregnated sorbents used in Climeworks and Global Thermostat modules. The bi-functional material presents moieties with high affinity with the CO_2 and this part of the material is active during the loading/uptaking phase. Other active sites are prone to catalyse the hydrogenation occurring during the chemical/reactive desorption of the material. According to their claims, the sorbent enables a reduction of the energy demand during CO_2 desorption and the performance of the module is like the Global Thermostat's one. In Susteon's module regeneration occurs in parallel with the methanation process. The methanation process is not included in the Climeworks technology. After each cyclic loading-regeneration loop, the captured CO_2 is not desorbed and released, but turned into methane through the Sabatier process over the active sites of the Ru-based catalyst dispersed in the adsorbent matrix: part is active in the CO_2 capture and part in the methanation when

[1] HIF is an affiliate of AME. 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 https://www.hif.cl/en.

Table 1
DAC technology suppliers: data sources/references and TRL assessment using the novel IEA guidelines for DAC technologies (companies are clustered as in Fig. 1).

Supplier (country)	Source(s)	TRL	Brief overview
Climeworks (Switzerland)	Beuttler et al. (Beuttler et al., 2019) Wurzbacher et al. (Wurzbacher et al., 2016) Gebald et al. (Gebald et al., 2015) CarbFix project ("Direct Air Capture - Carbfix," n.d.) Pearce, *Carbon Brief blog* (Pearce, 2017) Gertner, *The New York Times* (Gertner, 2019) Climeworks's webpage ("Mammoth: our newest direct air capture and storage facility," n.d.; "Orca is Climeworks' new large-scale carbon dioxide removal plant," n.d.)	8-9	• Technology validated on small-scale at Hinwi (Switzerland), Orca and Mammoth (Iceland) • Current cost of the capture 500-600 USD/t_{CO2}, with cost target of 200 USD/t_{CO2} by 2025 and below 100 USD/t_{CO2} by 2030 • 36 kt_{CO2}/y is the largest scale to be tested, but the target size is 100 kt_{CO2}/y • Transparent and reasonable learning-by-doing curve • Sorbent material (amine-functionalized solid)
Global Thermostat (USA)	HIF agreement (Thermostat, 2021) ExxonMobil agreement ("ExxonMobil expands agreement with Global Themostat sees promise in direct air technology," n.d.; "Global Thermostat Renews Agreement with ExxonMobil," n.d.) Leozio et al. (Leonzio et al., 2022) Kaufman and Rathi, *Bloomberg* ("A Carbon-Sucking Startup Has Been Paralyzed by Its CEO," 2021)	7-8	• Few disclosed details on the technology and well-defined plan for scale-up and validation the validation on large-scale • Impregnated honeycomb sorbent • Signed agreement with Exxon Mobil and HIF (commissioning started in 2022) • Claims that cost of DAC technology is below 100 USD/t_{CO2}
GreenCap Solutions (Norway)	GreenCap webpage ("Greencap Solutions," n.d.; "Greencap Solutions," n.d.) Some pieces of information were collected during a meeting between GreenCap representatives and the authors (MS Teams meeting on June 30th 2022)	6-7	• Development of own patented technology • Technology relies on commercial zeolite without any chemical treatment • Lower investment and maintenance cost • Validate at relevant scale (0.3 kt_{CO2}/y) for CO_2 utilization in greenhouse farming
Kawasaki (Japan)	Numaguchi et al. (Numaguchi et al., 2021, n.d.) Barth (Barth, n.d.)	4	• Novel amine-impregnated porous material resilient to fluctuations in operating conditions and air moisture • Small-scale piloting (5-6 kg_{CO2}/day) • Low-temperature regeneration (60°C) under vacuum condition (20 kPa)
Susteon Inc (USA)	Jeong-Potter et al. (Jeong-Potter et al., 2022) Arellano-Treviño et al. (Arellano-Treviño et al., 2019)	4	• Bifunctional catalyst for activate CO_2 removal from air and catalyse CO_2 methanation during the absorbent regeneration

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Table 1 (*continued*)

	Coppitters et al. (Coppitters et al., 2023)		• Loop occur within the same module (process intensification) • Still at prototype level • Only company offering carbon utilization instead of removal and storage
Carbon Engineering (Canada)	Keith et al. (Keith et al., 2018) Holmes and Keith (Holmes and Keith, 2012) 1PointFIve and Carbon Engineering agreement (Griffin, 2022; L, 2022) Other agreements and planned activities (Griffin, 2020, 2019)	7-8	• Technology benefit from economy of scale (i.e., suitable for large capture > 1 Mt_{CO2}/y) • Validation at large-scale still missing • Caustic solvent is used to capture CO_2 and regeneration occurs in a calciner (high-temperature process) • Technology currently validated below 0.5 Mt_{CO2}/y • Signed agreement (June 2022) with 1PointFive for construction of a fleet of 70 DAC facility of 1 Mt_{CO2}/y by 2035 • Best estimate suggests cost around 94-232 USD/t_{CO2}
Commonwealth Scientific and Industrial Research Organisation – CSIRO (Australia)	Kiani et al. (Kiani et al., 2020) Agreement with Rolls Royce ("Press releases," n.d.; Royce, n.d.)	4	• Amino acid solvent • Regeneration occurs at conditions similar to amine system (100-120°C) • Crossflow contactor as in Carbon Engineering to reduce pressure drop • Rolls-Royce exhibit interest to build a pilot plant for 100 t_{CO2}/y starting from June 2023. • Project budget of 3M£ • Estimated cost ranges 273-1227 USD/t_{CO2}, but it is more likely 676 USD/t_{CO2}
Bipolar Membrane Electrodialysis – BPMED (Not properly a start-up/company)	Sabatino et al. (Sabatino et al., 2020, 2021, 2022)	3	• Process developed starting from experimental data collected at lab-scale • Completely electricity-driven DAC • Preliminary assessment suggest 770 USD/t_{CO2} • Membrane improvement can drive the drop of the costs to 250 USD/t_{CO2} • Alternative to high-temperature Carbon Engineering regeneration
Mission Zero Technology – MZT (UK)	Webpage ("Our Technology," n.d.) UK Government agreement and financial support ("Mission Zero-led consortium win £3M government contract to pilot breakthrough DAC technology," n.d.)	4	• High selective ion membrane • Compact and modular technology • Lower cost for the regeneration thanks to weak Co2 bounding to the adsorbent surface and efficient electrochemical regeneration • Awarded a 3M£ UK government-funded project for pilot facility of 120 t_{CO2}/y
Verdox (USA)	Voskian et al. (Voskian and Hatton, 2019) Liu et al. (Liu et al., 2020) Diederichsen et al. (Diederichsen and Hatton, 2022) Wilcox et al. (Wilcox, 2020)	3-4	• Exploits electro-swing adsorption • High efficiency tested on a lab-scale apparatus • Lab-scale experiments suggests a competitive cost of the captured CO_2 (50-100 USD/t_{CO2}) • Ongoing prototyping and scale-up • Validation of a small prototype still missing

(continued on next page)

Table 1 (*continued*)

Oy Hydrocell (Finland)	Elfving et al. (Elfving et al., 2017) Vazquez et al. (Vázquez et al., 2018) Webpage ("Direct Air Capture (DAC) appliances," n.d.)	3-4	• VTSA system • DAC module looks like a plate-thin heat exchanger using functionalized resines • Prototype used in a small CO_2-to-fuels application (1.3 t_{CO2}/y processed)
Infinitree (USA)	Webpage ("Technology," n.d.) Leonzio et al. (Leonzio et al., 2022)	5-6	• Moisturizing steam-assisted desorption • Ion-exchange resin • Tested for 100 t_{CO2}/y for the niche market of CO_2 utilization in greenhouse farming
Skytree (EU agency - Netherlands)	Webpage ("Skytree | Indoor Farming," n.d.) Leonzio et al. (Leonzio et al., 2022)	5-6	• Concept similar to Infinetree • Captured CO_2 is fed algal biomass growth for biofuels production • Validated until 100 t_{CO2}/y (scale relevant for the algal culture application)

H_2 is injected during the regeneration phase. The technology is still under development at prototype level. The costs are not provided yet for this technology. A recent publication by Coppitters et al. (Coppitters et al., 2023) on 4E assessment is now available on a similar concept/process layout, but the analysis is still based on theoretical assessment. The concept could represent a relevant enhancement, but there are still open questions on extent of the intensification since part of the adsorption bed is sacrificed to include the CO_2 methanation catalyst.

In the solid-DAC process, the adsorbent plays a key role. A recent publication by Young et al. (Young et al., 2023) suggests that there are several aspects to account for when developing novel sorbent materials. Their machine learning analysis identified critical parameters and factors where research should produce more efforts. They found "*that mass transfer and kinetics within the design space of amine-functionalized adsorbent and can be optimized via adsorbent and contactor design. Meanwhile, the heat transfer also has a significant impact and should be improved through better adsorbent thermal conductivity, alternative contactor design, or different heating methods*". Another key point is the sorbent stability. As far as we know, there are no reports and outcomes from long time running suggesting after how many cycles the activity of the material degrades and the efficiency drops. This is an additional aspect that the technology validation in relevant industrial environment should address. Research produced and introduced innovative adsorbent (Shi et al., 2020; Zhu et al., 2022) that have promising future in DAC. Organic adsorbent and MOFs are acquiring attention due to high selectivity towards CO_2, humidity rejection, and higher stability. MOF with tailored properties could be used for the DAC purpose. However, this option has been validated only on a laboratory scale or screening level, so the industrial deployment is still relatively uncertain (Mahajan and Lahtinen, 2022; Marinič and Likozar, 2023). MOFs are still too expensive. A few of them are now produced on large scale (still small if compared to commercial sorbent), but the cost of production has not been reduced substantially (Mahajan and Lahtinen, 2022).

2.2. Solvent-based DAC

Carbon Engineering is a solvent-based technology company which benefits from the economy of scale; thus, it aims at building a large-scale DAC plant (>1 Mt_{CO2}/y) to reduce the levelized costs of the captured CO_2. The scale-up from small-scale to large industrial applications is time-demanding. In June 2022, 1PointFive (OXY) and Carbon Engineering announced a DAC deployment plan to enable global roll out of plants. Michael Avery, 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. Occidental Petroleum Corp., stock exchange listed as OXY, will facilitate the construction of 70 DAC large-scale facilities (1 Mt_{CO2}/y each) by 2035 through its low-carbon ventures unit 1pointfive and agreement with Carbon Engineering. The first plant will capture up to 0.50 Mt_{CO2}/y. This is 120 times bigger than Climeworks' Mammoth site. The start-up date has not yet been decided, but is likely to be in 2026. Large-scale validation in the field of Carbon Engineering is ongoing thanks to this agreement. Keith et al. report that solvent-DAC can lower the cost per unit of mass of the captured CO_2 and they estimated 94–232 USD/t_{CO2}.

CSIRO, the Australian research centre, is also studying an alternative. It is an amino acids-based absorption with large liquid recycling. The technology is different from Carbon Engineering. Indeed, high-temperature regeneration (calciner as in Carbon Engineering) is not suitable for preserving the solvent (amino acid) from degradation. The regeneration should occur at 100–120 °C as a conventional amine-based capture process. Instead, in CSIRO's alternative, the absorption process occurs in a system resembling a cooling tower. This technology is already available for piloting. In June 2022, Rolls-Royce exhibited an interest in the CSIRO technology and funded a research project for the small-scale pilot testing for 100 t_{CO2}/y to be started during 2023. At PCCC-7 (IEA Congress) in Pittsburgh in 2023, Rolls Royce representatives confirmed the ongoing pilot construction. Since the technology is not validated in a facility yet, the technology is still at low-TRL (i.e., TRL-4), but after the validation (TRL-6) it is likely that CSIRO could further scale-up the capacity of the process and achieve a pre-industrial configuration, i.e., TRL 7–8. The uncertainties associated with the CSIRO's alternatives are also reflected by Kiani et al. who reported that their techno-economic assessment suggests capture costs ranging 273–1227 USD/t_{CO2}, where 273 USD/t_{CO2} is the most optimistic price and 1227 USD/t_{CO2} is the most expensive and uncertain scenario. A reasonable estimate is 676 USD/t_{CO2}.

Carbon capture using solvent is a well-established process. Hence, the solvent-DAC can be seen as an advanced CO_2 capture process from a diluted source/flue gas: the solvent chemically bind the carbon dioxide and it is then regenerated at higher temperature. What really matters in absorption-based DAC is a correct design of the contactor in terms of gas velocity, contact flow pattern, and packing material (Keith et al., 2018). A more recent publication by Kasturi et al. (Kasturi et al., 2023) recommends that the packing type and configuration affect the performance of the DAC device and also the energy consumption due to pressure drop. This confirms findings in prior works aimed at improving liquid-based DAC (Mazzotti et al., 2013; Zeman, 2014). The corrosion may represent an additional problem. This issue is well-known for amine capture plant (Krzemień et al., 2016; Mazari et al., 2020). It is reasonable to assume that caustic solutions used in Carbon Engineering's technology may represent a problem which will lead to the need for special materials able to resist such corrosive environments. However, there are no works in the literature dealing with this aspect.

2.3. Electrochemical DAC

Verdox is an MIT start-up whose aim is to develop a fully electricity-driven DAC. The process exploits the electro-swing adsorption (ESA). Due to its configuration, the process is discontinuous and cyclical: in the first step the electrodes load the CO_2, and then they release the "adsorbed" when voltage is switched. The lab-scale validation shows that the faradaic efficiency of the process is high (>90 %) even after 7000 cycles. Verdox claims that its technology is flexible, and that it can be easily integrated into any process in a plug-and-play fashion thanks 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 makes 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}, but this preliminary estimate is based on lab-scale data. Verdox has started the prototyping of the ESA-DAC modules. There are no details available on how close they are to building the first small prototype.

Mission Zero Technology (MZT) is a young English start-up. MZT's solution adopts ion-selective membrane technology. According to what is advertised, the technology is compact, modular, electrically driven, and operates under ambient conditions ensuring continuous operation instead of cyclic as in Climeworks. Moreover, MZT claims that the peculiar features of the ion-selective membrane could drop the costs due to the weaker bonding of the CO_2 on the capturing material compared to competitors. The weaker interaction between sorbent and CO_2 leads to lower energy demand for the regeneration. Further, the electrochemical separation consumes 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. In 2022, the Mission Zero-led consortium was awarded a £3M UK government contract to pilot (120 t_{CO2}/y) DAC technology. As most of the companies active in the sector, MZT do not report any costs associated with the proposed technology.

Sabatino et al. developed a full-scale DAC plant simulation and assessment for the first time using Bi-Polar Membrane Electro-Dialysis (BPMED) technology in 2020 with lab-scale experimental data in previous work by Eisaman (TRL 1–2) to assess the economics of this novel technology. BPMED could drive the full electrification and decarbonisation of DAC if powered by renewables. The preliminary levelized cost of the BPM-based process was 770 USD/t_{CO2} due to the high cost of the membrane, the large electricity consumption, and uncertainties on the lifetime of the materials. Recently, they investigated the possibility of cost reductions in the future through experience, material performance, and electricity price reduction. 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. The authors showed an alternative to calcination and the process scheme looks more compact and modular than the Carbon Engineering solution.

Compared to solid- and liquid-based DAC, electricity-driven DAC, such as electro-swing adsorption and bipolar membrane, is an immature technology and is tested only at laboratory scale. This implies that this option looks unlikely to be ready for a fast industrial development and deployment by 2030 when the first significant emissions cut is planned.

2.4. Other/hybrid options

Hydrocell Ltd. was founded in 1993 and collaborates with the VTT research centre in Finland to develop a VTSA system for DAC. The DAC unit looks like a thin plate heat exchanger. The unit is composed of several short beds each containing an active CO_2 adsorbent, an amine-functionalized polystyrene resin. Brush-type heat exchangers are immersed in the adsorbent beds for heating the beds during the desorption phase. After the adsorption step, the cleaned air is removed from the bed using vacuum pumps (0.02 mbar abs). Then, a warm glycol–water mixture, heated in a boiler, is conveyed to the brush-type heat exchanger for heating and partially desorbing the captured CO_2. After the preheating stage, CO_2 is collected from the bed. The described prototype has been tested for CO_2-to-fuel process. The DAC technology is a modular adsorbent system whose capture capacity is 1.3 t_{CO2}/y per module. A cost estimate for the captured CO_2 is still missing.

Infinitree, founded in 2014, is another start-up in the field of DAC. It is active in the niche market of urban farming with small-scale applications. It exploits moisturizing desorption which looks like 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 technology, moisture swing adsorption using ion-exchange resins, has so far been tested for a capacity of 100 t_{CO2}/y.

Skytree's concept is resembling Infinitree's solution in terms of technology and market of interest. Skytree aims at providing the captured CO_2 to algal culture for biomass growth. Skytree is a Dutch spin-off from European Space Agency (ESA). It was founded in 2008 and the technology relies on electrostatic adsorption and moisturizing desorption at 80–90 °C. Unfortunately, little information is available about the start-up and in general for moisture-driven electro-adsorption. As for Infinitree, they have tested a 100 kt_{CO2}/y capture facility. For both Infinitree and Skytree, an estimate of the costs is not available.

Fig. 1 outlines the current TRL for each technology using sources gathered in Table 1. In Fig. 1 the technologies are clustered according to the CO_2 sequestration mechanism. The reference scale for the TRL is reported in the IEA report on DAC technology published in 2022. Differently from the conventional TRL ladder (TRL 1–9), IEA extended the upper part adding two layers, TRL-10, −11. The added TRL layers stress the industrial application introducing relevant shades to discriminate the industrial maturity. The added layers are essential for our assessment because they focus more on the market rather than the technology itself (Direct Air Capture 2022 *A key technology for net zero*, 2022). These further TRL levels directly affect the deployment, thus the impact of DAC as CDR to match the ambitious environmental target for 2030. Indeed, TRL-10 ('*solution is commercially available and competitive but needs <u>evolutionary</u> improvements to stay competitive*') introduces the concept of competitiveness. TRL-11 claims the full proof of reached stability that is directly associated with predictable growth and planning for the deployment. Technology is fully developed only when TRL-11 is reached, and it is sustainable in itself without government aids or other incentives.

Fig. 1 shows that Climeworks is the only company close to the industrial deployment of a fully developed solution (TRL 8–9). Limiting our comments to suppliers working on large-scale facilities, Global Thermostat solutions are already available on the market. Noteworthy, GreenCap Solutions aims at entering the market with small-middle plants for CO_2 utilization in greenhouse farming. Global Thermostat's target is large-scale CO_2 capture (0.1–0.5 Mt_{CO2}/y). This means that Global Thermostat still misses the validation in relevant industrial clusters adopting large-scale pilot plants (capacity > 10 kt_{CO2}/y). As a general comment, adsorption DAC looks more mature compared to other options even if solvent-based DAC is close to the industrial validation. As for Global Thermostat, the validation on large-scale and relevant industrial environments is missing.

For solvent-based DAC, Carbon Engineering has the most mature

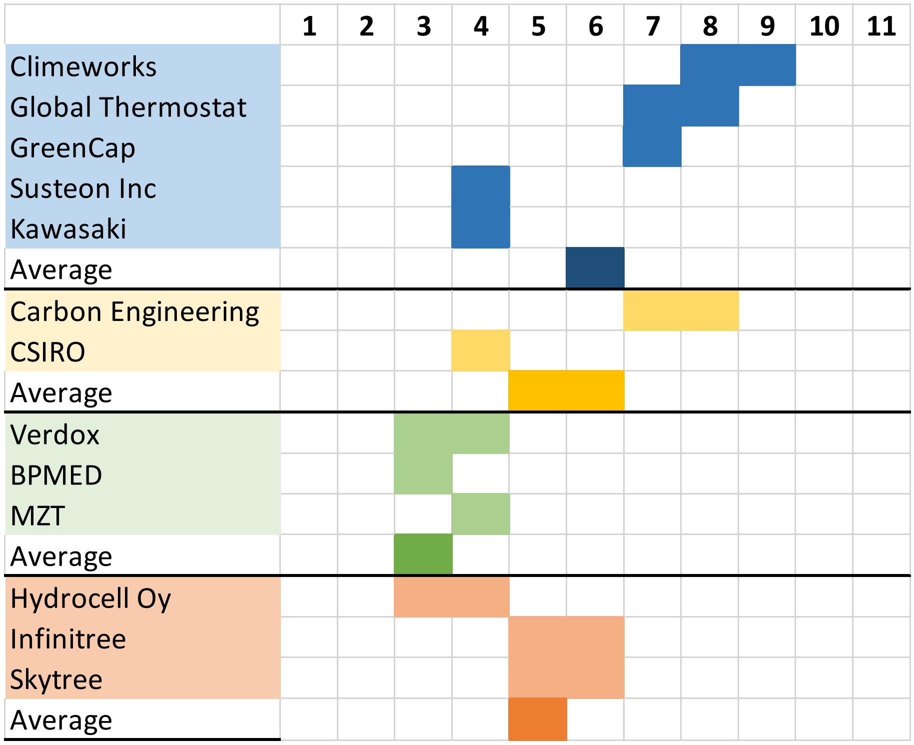

Fig. 1. DAC commercial technologies according to novel IEA's TRL scale. The technologies are clustered according to the CO_2 capture main mechanism: adsorption (blue), absorption (yellow), electrochemical process (green), and other/hybrid processes (orange). The hybrid process includes DAC solutions for small-scale applications where moisture-assisted regeneration is applied using waste heat. Also, the chart provides the 'average' TRL for the clusters of DAC technologies.

technology (TRL 7–8). Noteworthy, liquid-DAC benefits from the economy of scale, thus sizes larger than 0.5 Mt_{CO2}/y are desirable. The new agreement with Occidental Petroleum Corp./1PointFive in 2022 incentivized the validation of the solvent technology on a large scale (>0.5 Mt_{CO2}/y) by financing both scaling-up activities and the technology deployment. CSIRO's DAC technology takes advantage of consolidated amino acids solvent for CO_2 capture. Amino acids are well-known to be active in CO_2 capture and they have already been used and tested for the scope. Differently from Carbon Engineering, CSIRO's researchers pointed out that the associated costs are quite substantial. Rolls-Royce financed the first pilot plant to test the concept despite the high costs that could hamper the research for this technology.

Electro-swing adsorption (Verdox) and bipolar membrane electrodialysis (BPMED) are fully electrified solutions. The latter represents a plug-in for the Carbon Engineering process to turn the regeneration into an electricity-driven layout. These options represent the future of the DAC. However, at the current state, these processes must be validated on a small prototype. The costs for the BPMED are still high due to electrical energy consumption and membrane material. Novel and more economic materials could benefit the overall economic balance. Verdox looks to have a promising technology as they are cost-competitive compared to other solutions. The concept has been validated on the lab scale using a small device, but the validation of the estimated costs of the scale-up is missing. Among the startups active in the field of electro-swing adsorption, MZT looks to be one of the most propositional companies on the market. They recently got funds from the British Government, £3M, to validate their technology. MZT's module is not fully disclosed, but the company states that the preliminary tests are encouraging, and their technology could fix some of the problems associated with adsorption such as discontinuous operation and energy demand for the adsorbent regeneration.

We also listed alternatives as other/hybrid processes. For this process, there is no literature is available, and the web pages are also poor in detail. For this reason, we do not extensively discuss these options.

Major concerns arise when assessing the time required for today's DAC technology to reach TRL 10 and 11. Therefore, we should seek to answer two questions: (1) how many years the full development of DAC technologies as a consolidated technology with TRL-11 will take and (2) the amount of time required for its deployment to get a few gigatons capture volume worldwide by 2050 (i.e., deadline for net-zero emission) and probably before, thus, by 2030. These two questions are crucial to state the contribution of DAC as CDR to contrast climate change and sustain mitigation actions against CO_2 emissions. The first answer is not straightforward. Recent publications by Buchner et al. investigating the role of the TRL in the chemical sector pointed out that "*the time required for an innovation to pass from ideation to commercialization is relatively long compared to other fields of industry (up to about 10 years)*" (Buchner et al., 2019, 2018). The same analysis was limited to the conventional NASA's TRL scale, TRL from 1 to 9. Thus, as a rough rule of thumb, we could assume one year per TRL level single-jump in sectors other than chemical. This is not correct and unrealistic: reaching the last levels in the TRL scale is even more difficult and time demanding. Thus, time and resources, such as human and investments, allocation is not linearly proportional while moving bottom-upwards in the TRL case: the higher the TRL, the larger are the efforts and time to be spent. High TRL technology validation (TRL 8–9) stages are often the bottlenecks of industrialisation and could be unsuccessful (Daim et al., 2014; Roh et al., 2020; White et al., 2022). Moreover, DAC is a relatively disruptive and unconventional process where diluted CO_2 is recovered from a gas stream and purified (purity > 95 %). There are no similar processes in the industrial chemistry sector where purification is tailored for a single compound in a gas stream from ppm concentration to almost pure compound for either transport and storage or utilization. It is reasonable to expect that its development could face more challenges and hurdles. For instance, the jump from TRL-9 to TRL-11 could be even more time-consuming for DAC technology if the aim is to make DAC technology a consolidated and standalone process (Direct Air Capture 2022 *A key technology for net zero*, 2022). This is very relevant when looking at the current state of the energy consumption and the associated costs that make it less appealing than conventional CO_2 capture from flue gas. Indeed, we should contextualize the DAC development to the current geopolitical framework where energy costs are increasing, and this could slow down the deployment of large-scale DAC facilities. Further, two surveys distributed both to experts in the field as in Sovacool et al. (Sovacool et al., 2022) and non-expert people as in Cox et al. (Cox et al., 2020) emphasised that the DAC deployment is not merely a technical problem, but its deployment involves financial (investments), political (legislation and active support), and social sciences (acceptance from non-technical people). Sovacool et al. state that political support through incentives cannot be further postponed if environmental goals are to be fulfilled by 2030. Further, Shayegh et al. (Shayegh et al., 2021) supplied a survey to a poll of 18 experts in DAC technologies. They were also asked for choosing the best technology to match the 2 °C temperature increment by 2050. This underlines that also the scientific community is not fully convinced that DAC will be ready to play a part in 2030's environmental goals. It seems that 2030 is too close to have DAC affordable and ready for deployment of large-scale facilities.

The DAC deployment is projected to have longer time horizons and play a role after 2035. Indeed, a gigaton solvent-DAC facilities fleet will be realistically operated not before 2035 as planned by Carbon Engineering and 1PointFive. Climeworks' technology is suitable for small-middle scale (<1 Mt_{CO2}/y) and in 2024 it is building a facility that can capture 36 kt_{CO2}/y, simply for the technology validation and scale-up understanding. Beyond these additional braking factors and uncertainties, we would point out the role of the supply chain for the DAC deployment. The most ready-to-market solutions are Climeworks, Global Thermostat, and Carbon Engineering. Climeworks is going to start up and test its largest DAC plant (capacity of 36 kt_{CO2}/y) in 2023. Carbon Engineering plans several plants (capacity ranging 0.5–1.0 Mt_{CO2}/y) to validate its technology on a large scale (i.e., reaching TRL 9–10). Part of those plants will be operative in 2026 but the overall facilities fleet not before 2035. The mitigation of climate change requires gigatons of CO_2 capture volume ready-to-use. Thus, at the current state, thousands of DAC facilities should be built in seven years to effectively match the Paris agreement. This appears quite unrealistic if we consider the time to reach TRL-11, the material supply chain, the time required to build the DAC plant and all the facilities to make them operative, such as legislation and permissions, energy supply, transport pipelines for the captured CO_2, and so forth. Still related to the supply chain, the large volumes of the DAC units require large material consumptions. Deutz and Bardow (Deutz and Bardow, 2021) estimated that a sorbent DAC plant will have a consumption of roughly 7.5 g of adsorbent per kilogram of CO_2 captured. A couple of works pointed out the materials usage, especially concrete and metals, to build the DAC facilities. Madhu et al. (Madhu et al., 2021) estimate that a 1 Gt_{CO2}/y DAC plant requires from 17 Mt to 36 Mt of material, such as steel, concrete, copper, and aluminium, if liquid- and solid-DAC plants are built, respectively. The breakdown of the materials reveals that 4–6 Mt/Gt_{CO2} of steel, 12–29 Mt/Gt_{CO2} of concrete, 0.3–0.4 Mt/Gt_{CO2} and 0.6 Mt/Gt_{CO2} copper and aluminium are consumed. These values are close to 1 % (steel and concrete) and range 1–2 % (copper and aluminium) of the current global production of these materials. But, since the target is to contribute to gigatons of CO_2 removal from the atmosphere these percentages are expected to become substantial, especially for the metal market. Further, transition metals (mainly copper and nickel) and aluminium will become more and more significant for the green energy transition in the coming years as highlighted in the IEA report (March 2022) on the role of critical material in clean energy scenario ("Executive summary – The Role of Critical Minerals in Clean Energy Transitions – Analysis," n.d.; IEA, 2022): "*Electricity networks need a huge amount of copper and aluminium, with copper being a cornerstone for all electricity-related technologies [...] In the case of electricity networks, copper and aluminium currently represent around 20 % of total grid investment costs; higher prices as a result of tight supply could have a major impact on the level of grid investment*". Noteworthy, Madhu et al. and Deutz and Bardow focused on steel and cement. Considering the severe operating conditions, i.e. strong basic environment solvent-based DAC or BPMED, ionic liquid in ESA, and so forth, it reasonable to expect a large request for special alloys which contain mixtures of transition metals such as cobalt, molybdenum, chromium, manganese, and rare earth elements to quote a few. These are listed as critical minerals by IEA. For instance, to capture 1 % of the global annual GHG emission, Deutz and Bardow suggest that the market share of material for metals is around 0.01–0.03 %. Since, the DAC is expected to contribute in the order of tens of giga-scale worldwide (Sendi et al., 2022) and mega-scale at national level as showed in our recent work for Norway (Bisotti et al., 2023), it means that the DAC demand for metals easily reach 1–2 % of the current production. Unfortunately, the analysis does not cover all the critical materials identified in the IEA report. Critical materials are important in storage energy system such as batteries and accumulators to cope with discontinuities associated with most of the renewable energy sources as well as production and distribution of electricity. Moreover, some of these metals are also used in special alloys. Indeed, Madhu et al. analysis points out the need for ancillary infrastructures, such as (long) pipelines, electrical energy distribution, and supply chain of the materials. It is not possible to quantify the additional volume of construction materials from this work. However, it is quite clear that hundreds of thousands tonnes will be needed.

The green energy sector is planned to experience a relevant expansion and faster growth owing to climate actions. But IEA warns that the competition between several markets will increase the price of these minerals, and therefore also the expenses for capital investments like building material and energy infrastructure for DAC facilities. The same updated (2023) report on critical material ("Executive summary – The Role of Critical Minerals in Clean Energy Transitions – Analysis," n.d.) highlights that "*the market for energy transition minerals reached USD 320 billion in 2022 and is set for continued rapid growth, moving it increasingly to centre stage for the global mining industry. In response, investment in critical mineral development rose 30 % last year, following a 20 % increase in 2021. Among the different minerals, lithium saw the sharpest increase in investment, a jump of 50 %, followed by copper and nickel. The strong growth in spending by companies on developing mineral supplies supports the affordability and speed of clean energy transitions, which will be heavily influenced by the availability of critical minerals*". Then, the predicted increment in the demand for critical minerals in several key sectors could slow down the procurement of construction material and further delay the deployment of DAC facilities. This factor has not been pointed out in any reports yet. Furthermore, the recycling of these critical materials is still limited ("Forecasts," n.d.; IEA, 2022; Kalantzakos, 2020) and the market is dominated by China. Chinese companies control, depending on the metals, 40–60 % of the mines worldwide and up to 80 % of the metal post-processing. Also, reservoirs are in politically unstable nations ("Forecasts," n.d.; "Which are the critical materials within the battery industry?," n.d.; Nakano, 2021). What worries political experts and market analysts is the monopoly of the critical metals even when Chinese companies do not directly control the extraction, other Chinese subsidiaries control the purification, commercialization, and distribution of these materials to the market. As mentioned, the monopoly on the supply chain of these strategic metals is undesired since this could further slowdown the development and deployment of carbon dioxide removal (CDR) technologies ("China controls the supply of crucial war minerals," n.d.; "China's Role in Critical Mineral Supply Chains | German Marshall Fund of the United States," n.d.; Home and Home, 2023).

3. Piloting and technology development

When novel technologies proceed in development, the process of implementation and improvement is described according to the learning curve. This is a common feature for all industrial processes and DAC is

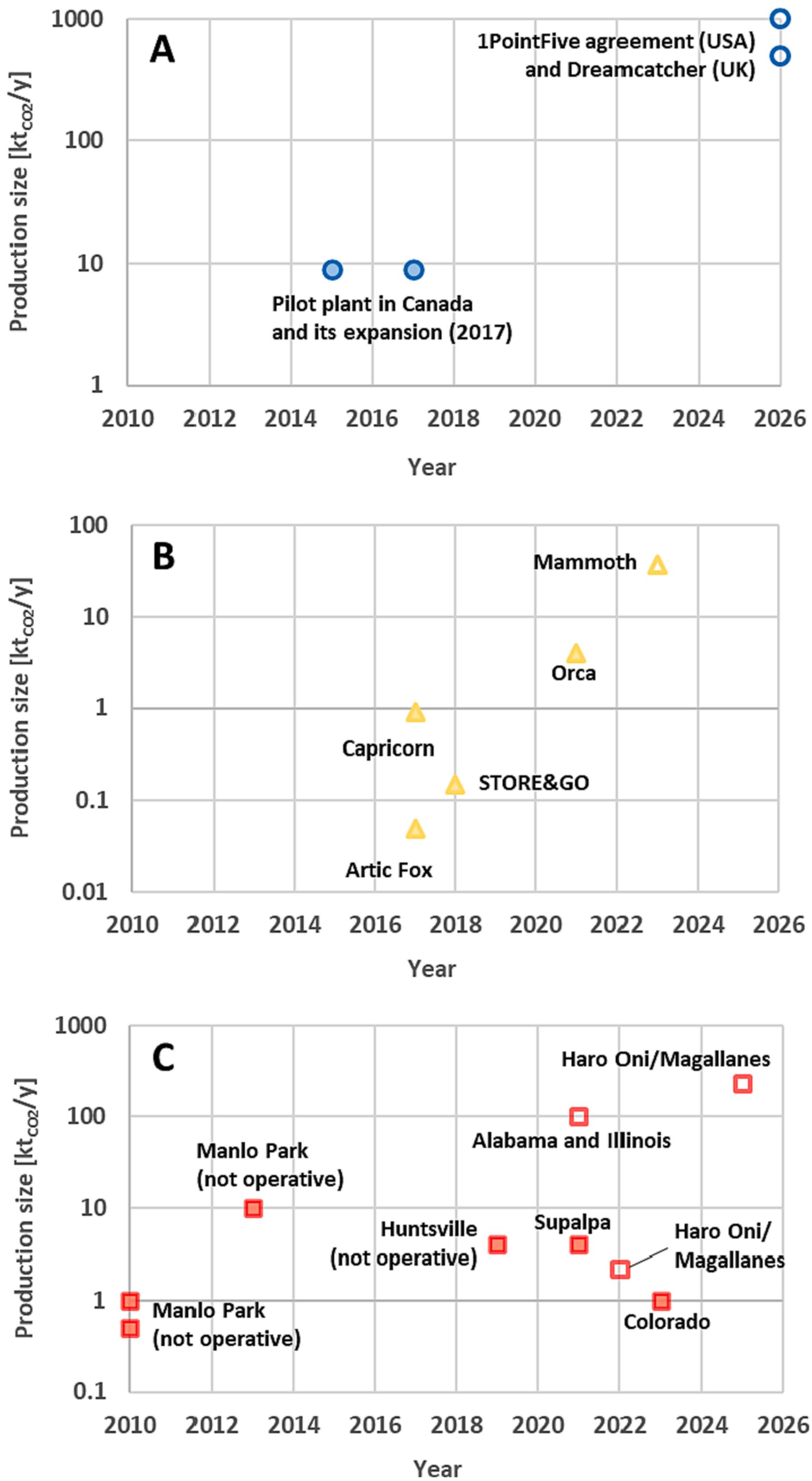

Fig. 2. Pilot plant sizes for technology scale-up development and validation (log-scale for y axis) for solvent-DAC Carbon Engineering (A), solid-based DAC Climeworks (B), and Global Thermostat (C). Solid marker for operating or build and dismissed facilities, void marker only for plants under construction (updated to April 2023), planned plant but not build yet or under design phase. Details are reported in Table 2 and Table 3.

likely to follow the same pattern of the learning-by-doing as highlighted in McQueen et al. (McQueen et al., 2021). Under this methodology, the supplier is supposed to acquire more and more confidence with the technology due to a progressive understanding of the process which favours the scale-up process and the reduction in costs. The learning process is continuous and gradual so that the scale-up follows different intermediate steps from the pilot scale-up up to the industrial demonstrative plant. This could be different for modular solutions, such as Climeworks and Global Thermostat, because the scalability is easier. However, it is not straightforward and issues could arise also when modular technologies is scaled up from few tonnes to a megaton as happened in 2021 and reported in a Bloomberg focus on Global Thermostat start-up ("A Carbon-Sucking Startup Has Been Paralyzed by Its CEO," 2021). Fig. 2 depicts the capacity of the pilot plants built by DAC companies during the development and validation stages for their own technologies. We focused on Climeworks, Global Thermostat, and Carbon Engineering since they are planning to build large-scale facilities. Also, their technologies look to be close to full validation in relevant industrial environments. The chart has been built upon data freely available in the literature, such as Ozkan et al. (Ozkan et al., 2022) and Sovacool et al. (Sovacool et al., 2022), and on the web pages of the companies themselves. Climeworks looks to have the only learning trend compatible with a conventional learning rate. The size of the pilot plants proportionally grows with the experience acquired in the previous campaign. Thus, in 2017 Climeworks started testing its module (0.05 kt_{CO2}/y) and the Orca plant (global capture capacity of 4 kt_{CO2}/y) was operated four years later (Gertner, 2019; "Orca is Climeworks' new large-scale carbon dioxide removal plant," n.d.). Now, Climeworks is building the Mammoth site having ten times the capacity of the Orca plant. It is not unlikely that the first large-scale (100 kt_{CO2}/y) Climeworks' DAC facility may be operative in 2024–2026 if the development and learning rate is kept at the current level. Conversely, a similar linear path is not detectable in the development of Global Thermostat and Carbon Engineering (see Fig. 2). Any information for middle-size pilot plants is missing. They seem to be scaling up their solutions without testing any intermediate scales. As an example, Carbon Engineering validated the liquid-DAC solution on small scale (10 kt_{CO2}/y typical of TRL = 4–6) between 2015 and 2020, but only in few years (e.g., from 2026) they would operate 1 Mt_{CO2}/y which is the target of the company. This implies an increment by two orders of magnitude for the plant size. Similar considerations hold for Global Thermostat. The most relevant achievements are the agreements signed with Exxon Mobil and HIF. Exxon Mobil asked for the commissioning of two DAC pilot plants in 2020 and it will contribute to advancing the scale-up of Global Thermostat's capture technology. The agreement has been renewed recently (April 2022). 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 1.0–2.0 kt_{CO2}/y. In April 2023, Global Thermostat commissioned a 1.0 kt_{CO2}/y facility (see Fig. 1) (Thermostat, n.d.). Remarkably, Global Thermostat is proposing also large-scale facilities (>100 kt_{CO2}/y) in Alabama, Illinois, and Chile (Manganelles/Haro Oni site) without any experience for middle-size plants (i.e., range 10–100 kt_{CO2}/y). Indeed, the Har Oni plant at Magallanes (Chile) was planned for small scale prototype (e.g., 2.2 ktCO2/y) in 2022, but the plan is to increase the size by two orders of magnitude (230 kt_{CO2}/y) without any further validation or gradual increment in the capture capacity volume in 2025, thus, over a couple of years, as reported in Sovacool et al. (Sovacool et al., 2022).

For a comprehensive overview, all the commissioned and still operating DAC facilities are displayed in Table 2 and Table 3. Table 2 reflects the current situation of the DAC plants, while Table 3 provides a more general overview of the built facilities and planned plants in the coming years/decade. The information comes from IEA DAC (Direct Air Capture 2022 *A key technology for net zero*, 2022; IEAGHG, 2021b) and Ozkan et al. (Ozkan et al., 2022) for Table 2, and Sovacool et al. (Sovacool et al., 2022) mainly for Table 3. Additional references on planned DAC plants have already been cited in the previous section. The tables are updated per 2022. However, as emerged from previous comments, there are no other large DAC facilities (capture volume > 0.5 Mt_{CO2}/y) planned after June 2022. For instance, Global Thermostat signed a research contract in 2021, but there has been no further news on the pilot plant construction and commissioning. The most recent agreement is the contract between 1PointFive and Carbon Engineering (June 2022).

Noteworthy, if we account for the volume removed by active DAC pilots in 2022 around the world, the total capacity is poor and negligible (around 26.5 kt_{CO2}/y as displayed in Table 2). If we in addition consider only the planned plants by Carbon Engineering, the capacity raises to 70 Mt_{CO2}/y which corresponds to 0.35 % of the planned emissions cut by 2030 (i.e., 20 Gt_{CO2}/y when the less stringent 2 °C temperature increment scenario is weighed). 70 Mt_{CO2}/y of worldwide sequestered CO_2 corresponds to slightly more than 1.5 times the annual GHG emissions of Norway. Since Norway has one of the greenest and most sustainable

Table 2
DAC facilities deployment (updated per April 2022) using data coming from IEA reports (Direct Air Capture 2022 A key technology for net zero, 2022; IEAGHG, 2021b) and Ozkan et al. (Ozkan et al., 2022).

Company	Country	Sector	CO_2 disposal	Start-up year	CO_2 capture capacity $[kt_{CO2}/y]$
Global Thermostat	United States (Manlo Park)	R&D	Unknown	2013	10.0
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
Global Thermostat	United States (Huntsville)	–	–	2019	4.00
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	4.00
Global Thermostat	United States (Sapulpa)	Power-to-X	efuels	2021	4.00 (2 plants of 2 kt/y each)
Global Thermostat	Magallanes (Chile)	Power-to-X	efuels	2022	2.20

Table 3
Status of key and upcoming Direct Air Capture technology providers updated to 2022 (table built using data reported by Sovacool et al. (Sovacool et al., 2022) and other sources cited in Table 1).

	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
		Canada	After 2026 (planned)	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 (planned)	Preliminary design and engineering phase for DAC plant removing 0.5-1 Mt_{CO2}/y	
	AtmosFUEL	UK	2030 (under discussion)	Feasibility study for 100 million litres of fuels per year	Start of operation planned for the end of the decade
		US	Starting from 2024 (planned) and accomplished by 2035	Construction of a fleet of 70 DAC large-scale plants (0.5-1 Mt_{CO2}/y)	In June 2022, 1PointFive (OXY) and Carbon Engineering announced a DAC deployment plan to enable global role out of plants. Occidental Petroleum Corp. (stock exchange listed as OXY) through its low-carbon ventures unit 1PointFive and Carbon Engineering agreement will lead to the construction of 70 DAC large-scale facilities (1 Mt_{CO2}/y) by 2035. The first plant will capture up to 0.50 Mt_{CO2}/y of CO_2 (120 times bigger than Mammoth site).

(continued on next page)

Table 3 (*continued*)

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 litres 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 litres of aviation fuel per day	Based on 2019 feasibility study, a proof-of-technology plant is planned. Current phase announced in 2021, no further update since.
	Mammoth	Iceland	Under construction	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

(continued on next page)

Table 3 (*continued*)

Global Thermostat (adsorption)		USA	2010 -2013	Proof of the technology	Menlo Park (California) plant capacity 10 kt_{CO2}/y
		USA	2021 (signed agreement)	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 (signed agreement)	Construction of Power-to-liquid demonstration plants, capturing up to 2 kt_{CO2}/y	Demonstration plant by Highly Innovative Fuels (HIF) 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	After 2030	Design and engineering phase for flue gas	Technology is meant to work with flue and ambient gas, currently focused on aluminium smelter exhaust, planning for industrial scale by 2030. No thermal energy is needed. Probably, it is a small-scale prototype for the technology validation at a scale in a relevant industrial application.

energy grid, one of the most stringent legislation on emissions, and it is a primed country for GHG reductions, this assessment shows how negligible is the contribution of DACCS to cutting emissions (Bisotti et al., 2023). Further, since other main industrial DAC technology providers, such as Carbon Engineering and Global Thermostat, still operate below megatons, DAC technologies will contribute only to a negligible percentage of the total GHG emission cut. To add to this, at present, adsorption-DAC does not look to be suitable for such a large capture volume installed in a single plant.

Sovacool et al. proposed a more complete overview reporting a full historical development of DAC technologies focusing on the installed capacity. Table 3 lists the commissioned and planned DAC facilities for Carbon Engineering, Climeworks, Global Thermostat, and Verdox. Merging the information provided in the literature, it looks like DAC deployment is the business for a few companies active in the sector for almost 10 years. Other start-ups are entering the market, but they prefer to cover niches of the market where the most established companies, Carbon Engineering, Climeworks, and Global Thermostat, do not provide services or their technologies are not suitable for that specific application. For example, urban capture and greenhouse enhanced culture, as reported in Table 1. The only exception is Verdox. This start-up aims at developing its own technology (ESA) and competing with the mentioned DAC technology companies (Diederichsen and Hatton, 2022). Verdox is planning the ESA-DAC scale-up and implementation of demonstrative pilot plants in Norway.

Currently, the deployment of DAC facilities is limited and mainly located in Europa and less in North America (Table 2). However, most of the planned plants after 2021 are mainly located in the United States and the UK (Table 3). Canada has already planned DAC deployment since 2015 and now the Canadian government is intensifying its financial assistance to CCUS (including DAC) technologies. As a last comment, Table 3 reinforces that only small DAC facilities have been built until now even if larger facilities, up to 230 kt/y, are planned. However, there are no updates on the status; thus, it is not clear when commissioning will occur. In April 2023, Global Thermostat commissioned a 1 kt_{CO2}/y facility, not reported in Fig. 1, in Colorado (Thermostat, n.d.). A long time run validation is still missing for Global Thermostat, but still, the plant capacity is limited to a small scale of 1 kt_{CO2}/y. Generally, the captured volume of the planned facilities is smaller than 100 kt_{CO2}/y, excluding the agreement between 1PointFive and Carbon Engineering for a complete fleet by 2035. As far as we know, only Climeworks is appointing to deploy the largest DAC plants in a couple of years (36 kt_{CO2}/y). Thus, the jump to either higher- or large-scale solutions, such as > 100 kt_{CO2}/y, looks uncertain except for Climeworks because of their smooth learning-by-doing curve. Moreover, the current and planned overall capacity, a few megatons, is still negligible (Table 2) if the DAC technology is expected to take part in the decarbonization process and carbon removal plan by 2030 (Table 3) when removal of gigatons is planned.

4. Final comments: Which are the hurdles?

DAC represents a cutting-edge concept to reduce CO_2 emissions and it is undeniable that DAC embodies one of the most attractive CDR technologies to mitigate climate change. In our analysis, we intentionally disregarded any insight into the energy consumption, process efficiency, the carbon footprint of the energy that DAC facilities are supposed to consume, and any considerations on the costs of the captured CO_2. We have identified some additional elements that could decelerate and deflate the excitement around the industrial deployment of DAC technologies. We investigated the real technical gap and time delay between the current status, with TRL ranging 7–9 for the most developed solutions, and real industrial application, at TRL 11, according to the novel TRL guidelines in the IEA report on DAC. The novel TRL-scale is recommended for any disruptive new technology where prior scientific background is not sufficient for a fast and full understanding of the concept. The environmental targets are ambitious, but the 2030 deadline is approaching and the TRL jump from TRL 7–9 to industrial implementation is time-consuming. Furthermore, DAC deployment is not a mere technical matter, but it involves several branches of finance, political, and social sciences, as pointed out in recent reviews. This is an additional aspect that could slow down the support to facilitate and finalise DAC deployment. Also, the capacity of each single DAC facility is still limited to a few kilotons (Orca plant 4 kt_{CO2}/y and 10 kt_{CO2}/y Carbon Engineering pilot plant) if compared to the actual gigatons volume (14.4 Gt_{CO2}/y) that CDR technologies are expected to cover by either sequestrating or preventing emissions by 2030. Even though the pilot plants do not represent the real size that will be installed in the next large facilities, the future capture volumes are restricted to a few megatons as planned by the suppliers themselves. The expected maximum capacity is around 0.1 Mt_{CO2}/y for adsorption DAC, and 1.0 Mt_{CO2}/y for the liquid-DAC, which benefits from the economy of scale.

To succeed, thousands of small DAC plants should be under construction and operative within seven years from now. This brings out some concerns about the effective possibility to achieve this in such a large supply chain of construction materials and energy, possibly, from renewable sources. For instance, if we consider 1PointFive (venture unit of Occidental Petroleum Corp.) and Carbon Engineering agreement dated June 2022, the plan forecasts a global capture volume of a maximum of 70 Mt_{CO2}/y by 2035, thus later than 2030 and covering only a negligible percentage (less than 0.5 %) of the global expected emissions reduction. The ambition of Climeworks is to capture 1 % of the global carbon emission worldwide by 2030 as confirmed to *Carbon Brief* in 2017 (Pearce, 2017). This target looks very ambitious and probably over-optimistic also nowadays, in 2023, due to the status of the technology when accounting for energy consumption and volume capacity. The aforementioned limiting factors to the deployment including economic and political issues incurred in in the last months, such as Russia aggression in Ukraine, which causes a natural gas shortage and spikes in the cost of electricity and raw materials, also applies. Nevertheless, an updated (July 2023) press release by IEA tracks the development of DAC technology ("Tracking Clean Energy Progress 2023 – Analysis," n.d.). This report corroborates doubts and concerns on the capacity of the DAC development to reach a significant maturity for industrial deployment:

> *"Twenty-seven DAC plants have been commissioned to date worldwide, capturing almost 0.01 Mt_{CO2}/year. Plans for at least 130 DAC facilities are now at various stages of development. If all were to advance (even those only at the concept stage), DAC deployment would reach the level required in 2030 under the Net Zero Emissions by 2050 (NZE) Scenario, or around 75 Mt_{CO2}/year. Lead times for DAC plants range from two to six years, suggesting that deployment in line with the NZE Scenario could be achieved with adequate policy support. However, most of the facilities announced to date are at very early stages of development and cannot be expected to reach final investment decision and operational status without continued development of market mechanisms and policies to create demand for the CO_2 removal service they would provide."*

Beyond these comments on TRL and supply chain for the deployment of DAC facilities, the analysis of data provided by companies and published in the literature shows a discrepancy between conventional process development and installed pilot plant capacity. It seems that a "rush into things" is occurring. This could affect the scale-up of the DAC technologies because of missing intermediate validations of middle-scale pilots (capacity volume 10–100 kt_{CO2}/y), as well-established practices required in industrial research and development planning. We have shown that only Climeworks presents a conventional learning-by-doing curve, while Carbon Engineering and Global Thermostat do not seem to follow conventional steps while developing and scaling-up their plants. At least, their approach is not conventional especially if considering that DAC is a disruptive unconventional process. Further, the large requests for materials, especially metals, that compete with other important sectors of the green energy transition, can further stop the DAC deployment on an industrial scale. IEA listed many metals as critical in terms of extraction volumes compared to applications and market demand. DAC facilities will consume some of these, but the large volumes will need proportional quantities. The growth of the demand is not running with production and supply chain at the same rhythm in a market where China has the monopoly for the extraction, processing, and distribution. This is expected to be reflected in an increase of the price. Thus, DAC plant investment costs will experience a substantial increment. Further, the recycling of these critical materials is still limited.

To sum up: are we ready for industrial applications of DAC? It is almost impossible to give an indisputable answer. Considering the overall elements discussed here, there is little room and time for DAC technologies to jump the TRL scale, reach the gigatons scale with a stable and profitable operation, and effectively contribute to the UN environmental agenda. We will probably not be able to fulfil the Paris Agreement as highlighted in the recent publication by Gadi Rothenberg (Rothenberg, 2023):

> *"To quote the late David MacKay:≪If everyone does a little, we will only achieve a little≫. If all major governments would decide that carbon pricing must reflect the true cost of GHG emissions, things could change, but this will not happen anytime soon. We must realise that we will not reach the goals of the Paris Agreement in time to prevent climate change. Thus, in addition to investing in prevention, we should invest in adapting to living in a world with average temperatures that are substantially higher than pre-industrial times."*

The work critically points out that also governments and international institutes are responsible for more proactive policies to stress and promote actions and investments for effective decarbonisation. Also, there is an urgency for (1) carbon mitigation technologies ready for industrial application, (2) the deployment of alternatives to help in contrasting the effect of climate change, and (3) disruptive solutions. We already have options for abating GHG emissions and permanently storing the captured CO_2 in geological reservoirs/minerals or temporarily in molecules. For instance, CO_2 capture using solvents and monoethanol amine (MEA) and chilled ammonia technologies are already industrially applied (TRL-11) and MEA absorption is a consolidated benchmark for carbon capture and storage, CCS (Pellegrini et al., 2021). Also, CO_2-to-synthetic fuels (methanol or Fischer-Tropsch synthesis) are alternative paths (Bisotti et al., 2021; Fedeli et al., 2022). Probably, our analysis on the current state, built facilities, and planned plants, show that DAC will probably contribute to decarbonization and emissions reduction after 2035 and the entity of its contribution is still uncertain because the industrial deployment is still incomplete and uncertain. For instance, Climeworks and Global Thermostat have not announced any agreement like Carbon Engineering for large-scale facilities construction and operation yet. Carbon Engineering and Global Thermostat must be tested for long-time run campaigns and in a relevant industrial context. Or, at least, there is no evidence that this step has already been successfully accomplished. Further, for Carbon Engineering and Global Thermostat, the learning curve and process scale-up look unusual and not as smooth as for Climeworks. The step-by-step scale-up is one of the fundamental aspects in the process development and deployment. Rushing into things is not a good practice in the technology field.

Our work shows that there are several technical aspects that companies and researchers should improve before a solid industrial deployment of DAC technologies. Several alternatives in the CCUS field are already available on the market. This does not mean that we should definitively give up improving and developing novel disruptive solutions. This is not the message that we would like to trigger and convey with this work. But the scientific community and decision-makers should be more pragmatic and realistic since time is running out and we need to take more actions to invert climate change because it is reasonable that DAC will not fit or significantly participate (<1%) to match the environmental target by 2030 or even by 2035. Finally, we wish that this would be a useful review and overview on the status of industrialization of DAC technologies for academics, industry, and policy makers. It might frighten investors but may also stimulate other researchers to become more innovative.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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