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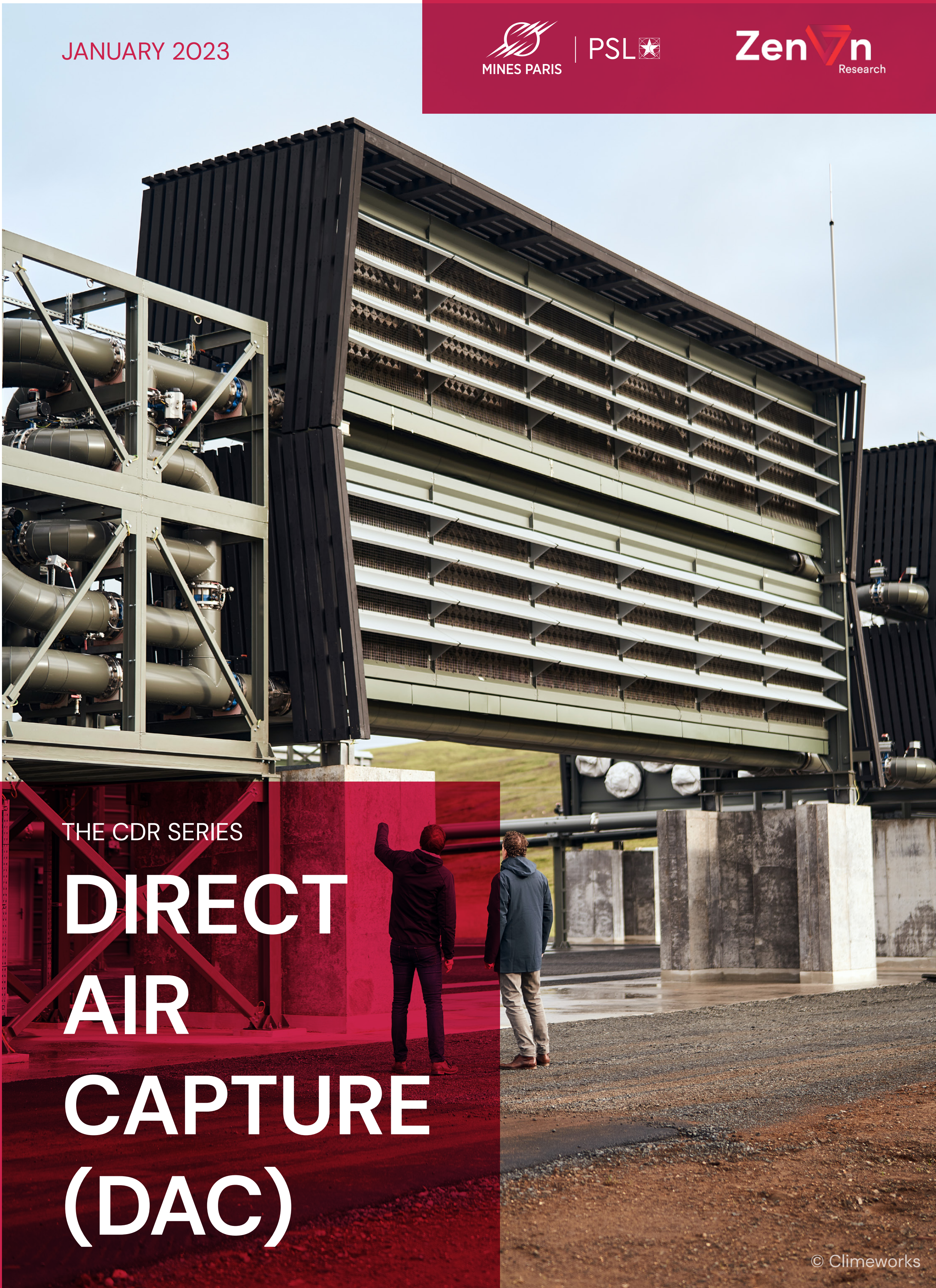

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THE CDR SERIES

DIRECT AIR CAPTURE (DAC)

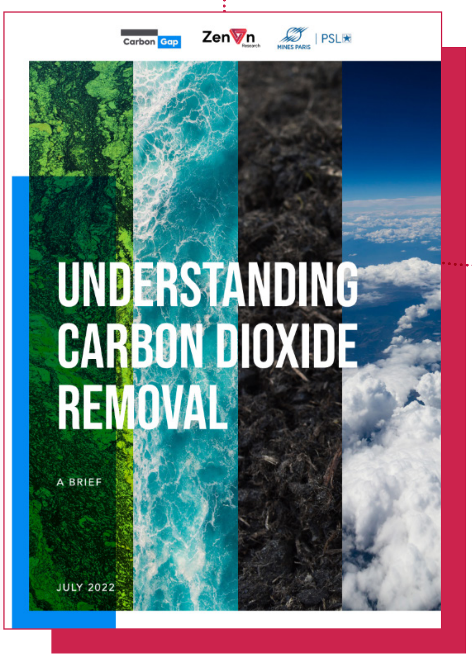
DIRECT AIR CAPTURE (DAC)

In the late 1990s, the idea of directly removing CO2 from the atmosphere via large mechanical 'filters' first emerged. Since then, various direct air capture (DAC) concepts have been developed and several projects have been implemented worldwide. In recent years, DAC has increasingly drawn attention, provoking a broad range of reactions – from enthusiastic supporters of the technology to sceptics who criticize its high energy costs or the risks of mitigation deterrence it presents.
How does DAC compare to other carbon dioxide removal (CDR) and carbon capture methods? Which role may this technology play in climate mitigation strategies? What are the key challenges for it to be deployed sustainably at large scale?

Contents

The CDR Series

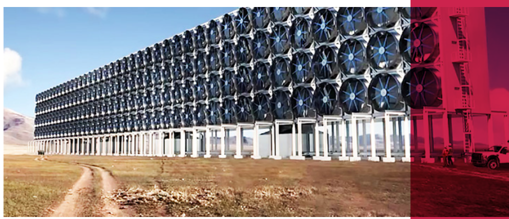
This report is part of a series on carbon dioxide removal (CDR) focusing on individual CDR methods and shedding the light on their specific characteristics, advantages and challenges. To get a more complete overview of the diversity of CDR approaches, we invite you to read the other reports of the series as well as our generic reports on CDR strategies.



HOW DOES DAC WORK?

Direct air capture (DAC) relies on chemical processes to remove CO_2 directly from the atmosphere. Firstly, ambient air is driven by fans through a contactor and encounters a material specifically designed to capture CO_2 molecules. In a second step, the regeneration phase, the CO_2 is released from the capture material and separated for being either sequestered or used[1].
Today, two main technology approaches have been developed, differing by the nature of the capture material: solid DAC (S-DAC) relies on CO_2 adsorption by highly porous sorbents with a very high specific surface area, and liquid DAC (L-DAC) that is based on CO_2 absorption by a basic solution, most commonly a hydroxide solution.

S-DAC plant (Climeworks' Orca plant in Iceland, running fully on renewable energy)
© Climeworks



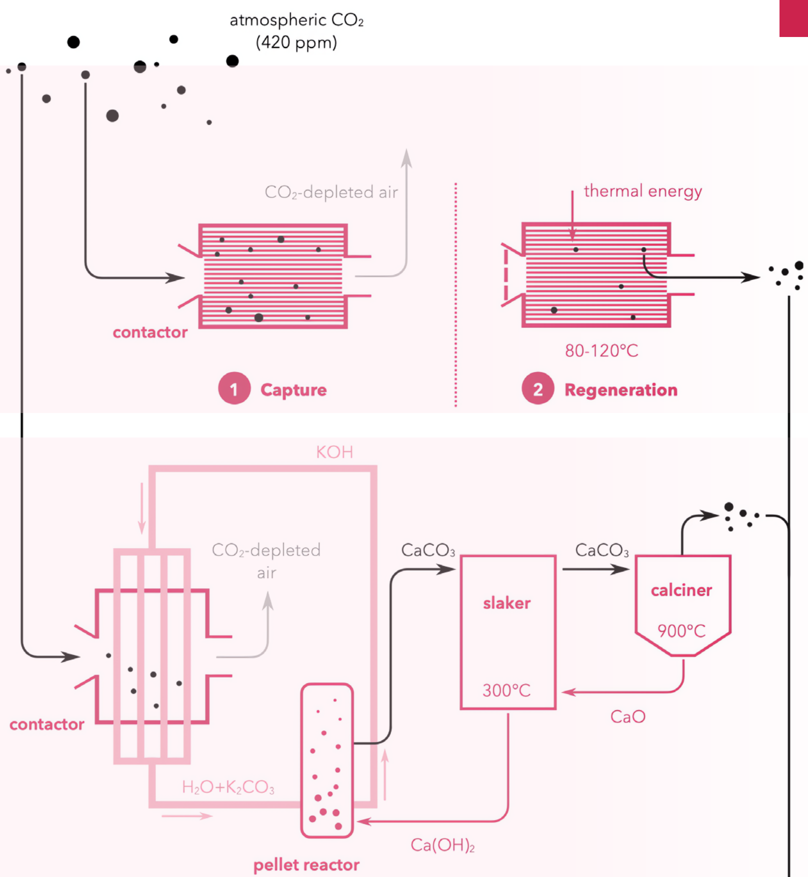
L-DAC plant
© Carbon Engineering

Solid DAC (S-DAC)

CO_2 entering the contactor binds to the sorbent's surface at ambient temperature and pressure. Once the sorbent reaches saturation, the contactor is closed off and isolated from the atmosphere, and the sorbent is regenerated (using either vacuum or thermal energy, or a combination of both), releasing the captured CO_2[1,2,3].

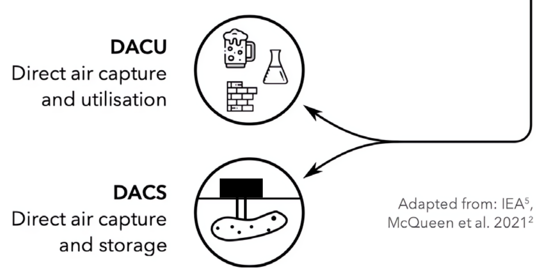
Liquid DAC (L-DAC)

Air is forced onto a flow of solvent (in this example, hydroxide) which reacts with the CO_2, forming water and carbonate salts. The solution is then fed into a pellet reactor together with calcium hydroxide ($Ca(OH)_2$), both regenerating the hydroxide solution and forming calcium carbonate ($CaCO_3$). The latter is then dried in a steam slaker and enters the calciner, where it is heated at high temperature (800- 900°C) to release CaO (led back to the slaker to regenerate the hydroxide) and CO_2[1,4].



What to do with the captured CO2?

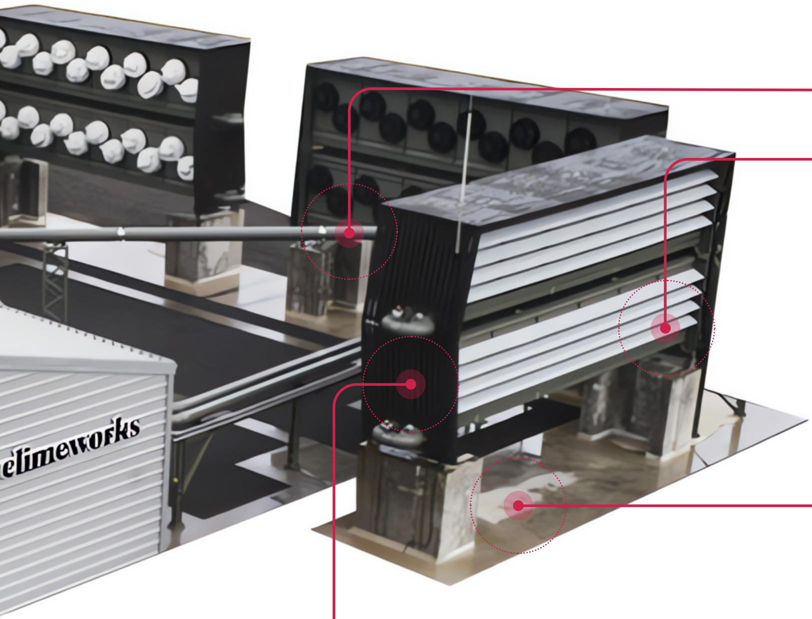
Air-captured CO_2 can follow two different pathways. A first possibility is to use it for a range of applications (DACU), either directly (e.g., in beverages or to fertilise greenhouses) or as a chemical constituent of novel products (e.g., synthetic fuels or building materials). The other option is to store the CO_2 permanently in geological reservoirs (DACS). For a comparison of DACS and DACU, see Climate outcomes of DAC.



Adapted from: IEA[5], McQueen et al. 2021[2]

DAC REQUIREMENTS AND IMPACTS

Today's DAC systems have specific requirements in terms of resources and can have a number of potential side-effects, both at local and global levels, all of which must be thoroughly evaluated to ensure environmental and social integrity[6,7]. This holds for any type of climate mitigation strategy that needs to be implemented at large scale and is key in establishing priorities between different actions. Choosing between different types of CDR methods, for example, requires regional circumstances that may or may not be conducive to large-scale DAC deployment (see Upscaling DAC)[8,9].



Water

DAC generally requires a few (up to 6) tons of water to capture one ton of CO_2 – at megaton-scale, this is similar to other industrial applications, and inferior to the other CDR methods[6]. Most water consumption serves to compensate for losses by evaporation during the regeneration phase (S-DAC) or the entire process (L-DAC)[12]. S-DAC can lead to net water production in some specific contexts (cool, wet climates), which is sometimes envisioned as a co-benefit[3,14]. Despite those moderate levels of water consumption, local impacts such as possible competition with other uses may not always be negligible, especially in water-stressed areas[6], and should be thoroughly assessed.

Materials

Infrastructure for DAC requires steel, concrete and plastics (for foundations and air contactors)[2,15]. DAC-induced demand for those materials will likely remain negligible compared to the projected global production[6,16]. Chemicals are another crucial feedstock: solvents and $CaCO_3$ for L-DAC, sorbents and substrates (copper, aluminium and alternative materials) for S-DAC[2]. Although most studies agree that the raw materials for sorbent production should not be an issue, the production of specialty sorbents at scale does not exist today – therefore, the ability to deploy the dedicated supply chains fast enough might be a bottleneck[2,6,16]. Issues related to the end-of-life disposal, recycling and ecotoxicity of materials have also been raised[17].

Energy

CO_2 is present in the atmosphere in highly problematic, yet relatively low concentrations (around 420 ppm or 0.004%[10]), which makes its direct capture a particularly energy-intensive process. While the minimal theoretical energy needed for extracting CO2 from the air is around 0.5 GJ/tCO_2[1], current technologies have requirements of about 4-10 GJ/tCO_2[11]. Both L-DAC and S-DAC require energy in the form of heat and electricity – about 80% and 20% respectively. Electricity is mainly used to power the fans, pumps, while currently, thermal energy serves to regenerate the sorbent/solvent[12]. The choice of the energy sources is strongly dependent on the local context, which might affect siting considerations in the future, and can have a significant impact on DAC carbon efficiency (see Box 1).

4-10 EJ

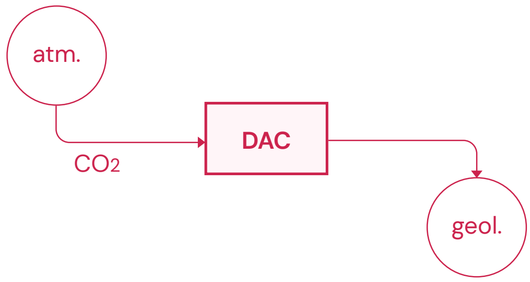
Energy required to capture 1 GtCO_2 with current DAC technologies. This represents **0.9-2.3%** of the world's 2021 final energy consumption (440 EJ[13]).

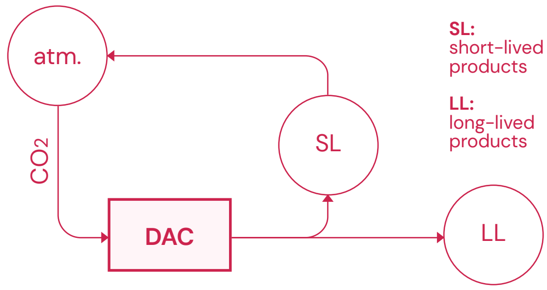
Land use

A megaton-scale DAC plant would require less than 1 km^2 of land. The total footprint of a DAC system would also include land area for an energy source to power the system and the type of energy used is a major factor in determining how much land is needed: land requirements are maximal for solar - or wind-powered plants (30-60 km^2/MtCO_2), which is 2 to 3 orders of magnitude less than biomass-based CDR, for example. A key advantage of DAC is that plants can be sited flexibly and on unproductive land, reducing competition with other uses such as food production[11].

DACS is one of many solutions to remove CO_2 from the atmosphere. Since carbon sequestered in geological reservoirs stays out of the atmosphere for several thousand years, DACS can provide negative emissions with a high level of permanence, making it a particularly interesting solution for removing CO_2 from the atmosphere (CDR). Other key advantages include the possibility to accurately monitor the quantities of atmospheric CO_2 being removed, as well as the ability to capture CO_2 continuously once the plant starts operations (as opposed to biomass-based solutions, whose capacity is dependent on biomass growth rate and timing).

DACU can create carbon-neutral products that do not require further digging of fossil carbon. Impact on the carbon cycle mainly depends on the longevity of the generated products, for CO_2 can return to the atmosphere after their utilisation. Products such as synthetic fuels made from air-captured CO_2 emit CO_2 back to the atmosphere after their combustion, and are thus at best carbon-neutral[17]. Apart from long-lived products that can provide negative emissions, such as cement mixed with CO_2, DACU mostly contributes to reducing emissions by preventing fossil carbon from being further extracted and ending up in the atmosphere in the form of CO_2.





BOX 1 | Is DACS carbon-efficient*?

To date, the number of exhaustive life cycle analyses (LCA) on operating DAC plants is limited[18]. Existing studies greatly differ in scope, some neglecting for instance the CO_2 transportation and storage steps[19,20]. There is a crucial need to establish unified frameworks to assess the environmental integrity of DAC based on real-world data as implementation progresses. Nevertheless, studies have shown that energy currently contributes the most to the carbon footprint of DAC plants, making low-carbon heat and electricity an imperative for DAC to perform in a carbon-efficient way[19]. This greatly affects siting considerations, making DAC mostly relevant in regions with already abundant low-carbon energy, or with high potential. Notably, heat pumps, geothermal sources, industrial waste heat or nuclear power[21] could provide the thermal energy required for S-DAC. Decarbonizing high temperature processes such as those involved in L-DAC, however, is more complex (see Technology perspectives). Low-carbon electricity will be crucial to both approaches, possibly supplied either from the local grid or from a dedicated power plant. When powered by low-carbon energy, DAC can achieve life cycle carbon efficiencies of 85-95%[5,22,23].

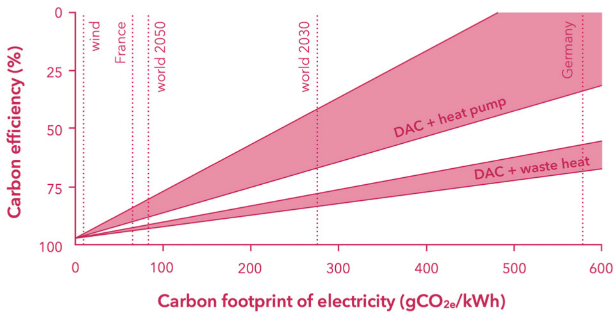


Fig. 1. S-DAC carbon removal efficiency depending on the carbon footprint of electricity supply (cradle-to-grave). Adapted from Deutz & Bardow 2021[17].

*Life cycle **carbon efficiency** can be defined as the 'relative net amount of CO_2 captured by the system, taking into account the GHG emissions, expressed in CO_2 equivalents, caused by the construction and operation of the DAC system'[24].

STATE OF THE TECHNOLOGY

TRL
≤6–7

Technology Readiness Level (IEA scale[5])

DAC is a nascent technology. As of 2022, 19 DAC plants have been built around the world, totalling about 10,000 tonnes of CO2 captured every year[5]. Currently, 3 companies are leading the market (Climeworks, Global Thermostat and Carbon Engineering), making S-DAC and L-DAC the most advanced technology subvariants (TRL 6), while a number of companies focus on developing alternative technologies, still at the laboratory scale (TRL 2-5, see Technology perspectives). Historically, most of DAC capacities have been focusing on CO2 utilisation, although the number of initiatives to sequester the captured CO2 is increasing[18].

Involvement from the private sector has grown massively over the past few years, in part driven by growing interest in net-zero commitments. DAC attracts an increasing number of investors, notably from venture capital and private equity. Significant deals have been concluded recently, with a record $650m raised by Climeworks in 2022. Some companies, such as Microsoft or Shopify, as part of their decarbonization strategies, have also been purchasing anticipated carbon credits for DAC removals that have not occurred yet, willing to support the early deployment of the technology[25].

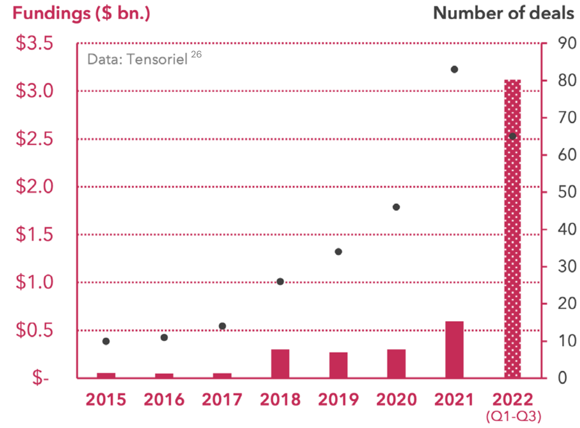


Fig. 2. Investments in DAC have risen massively over the last years, notably in the private sector.

Governments have also started to support DAC through public policies and funding. Although only few DAC-specific initiatives exist to this day, some mechanisms that cover diverse decarbonization or CDR initiatives may be adapted to DAC[5].

United States	45Q tax credit Carbon Negative Shot Regional DAC hubs
European Union	*Horizon Europe* *Innovation Fund* *Sustainable Carbon Cycles*
United Kingdom	Net Zero Strategy BEIS funding

Table 1. Government initiatives to support DAC development (in italic: potential or future, currently not used for DAC).

BOX 2 | DAC and CCUS*

CCUS has been investigated for decades to capture CO2 from point sources (industrial or power plants). Some technologies have reached high levels of maturity, although they have not been deployed massively yet. While DAC can to a certain extent benefit from this past experience, CO2 is much more diluted in the atmosphere than in industrial exhaust gases (by about 2-3 orders of magnitude)[1]. This results in higher energy requirements for DAC (see Figure 3) and makes it challenging to adapt existing CCUS technologies for this purpose[18]. In terms of siting, CCUS is inherently bound to industrial plants, often requiring large units, while DAC is theoretically less constrained thanks to its greater flexibility (although upscaling the technology may lead to further constraints)[27]. Another major difference lies in the climate outcomes of both strategies: DACS can contribute to removing CO2 from the atmosphere, while CCUS provides negative emissions only if used on a bioenergy plant (BECCS). DAC and point-source CCUS thus follow substantially different dynamics and have differentiated roles to play. However, many scenarios highlight that both may be crucial to mitigation levers, and should be considered as complementary rather than either/or solutions[28].

*Carbon capture and utilisation/storage

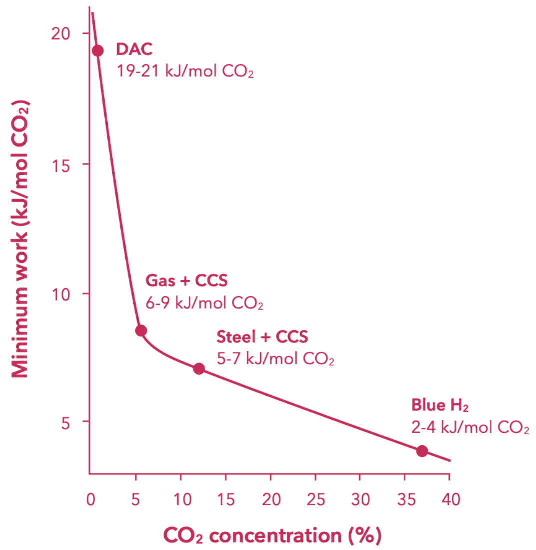
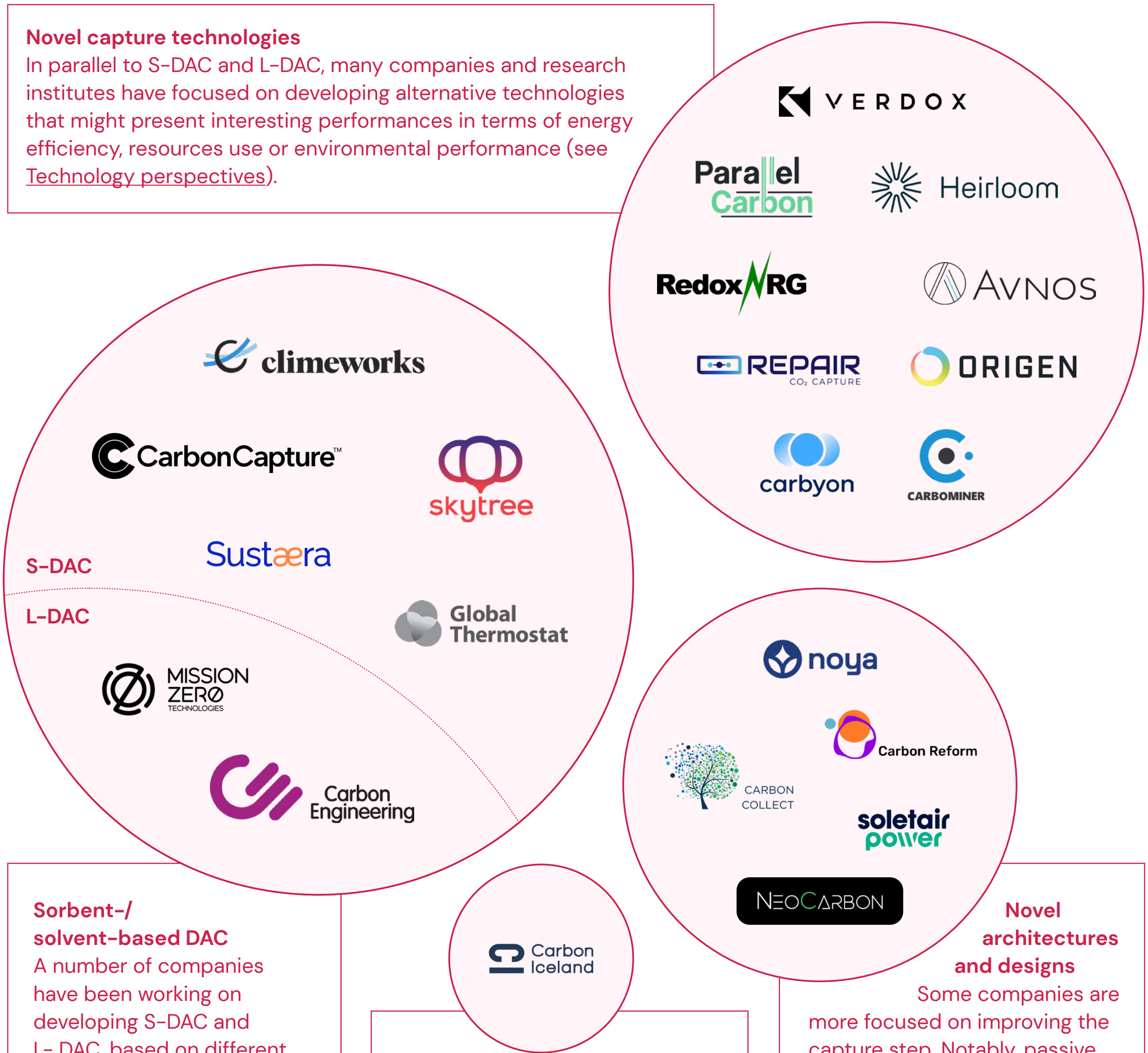


Fig. 3. Minimum energy requirements of DAC compared to those of other CCUS technologies. Adapted from Wilcox (2012)[1].

Companies focusing on DAC are flourishing. The DAC industry is mainly composed of companies developing their own in-house technology. Most of them are start-ups or spin-offs issued from or collaborating with research institutes and universities. Some also develop their own routes for geological storage or carbon utilisation in parallel, or work closely with related companies. The DAC ecosystem also comprises actors that focus on more functional aspects of DAC technologies, as well as companies that develop and implement DAC projects.

Novel capture technologies
In parallel to S-DAC and L-DAC, many companies and research institutes have focused on developing alternative technologies that might present interesting performances in terms of energy efficiency, resources use or environmental performance (see Technology perspectives).



Sorbent-/ solvent-based DAC
A number of companies have been working on developing S-DAC and L- DAC, based on different combinations of sorbents, solvents and processes. This includes the three companies that are currently leading the DAC market (Carbon Engineering, Climeworks and Global Thermostat).

Project development
Companies that focus on the successful implementation of DAC projects (identifying key siting opportunities and challenges, ensuring the economic viability of planned DAC plants, etc.).

Novel architectures and designs
Some companies are more focused on improving the capture step. Notably, passive DAC refers to systems that do not require additional energy to circulate air, either based on special- shaped contactors or on implementing DAC in already-existing infrastructure (cooling towers, buildings ventilation...)[29].

DAC COSTS

Today's DAC systems are expensive. This mainly results from the novel character of the technology as well as its high energy requirements. A wide range of estimates can be found, highlighting the lack of coordinated approaches to calculate costs with unified boundaries and assumptions[11,27]. Values found in the literature range from $200 to $1000 per captured tonne of CO_2 for FOAK* DAC plants, with estimates stemming from actors of the DAC industry generally on the lower side[30]. Such high costs are well above current carbon prices and are overall on the high end of the capture costs of CDR methods[27]. DAC costs are expected to decrease in the next decades as a result of wider deployment and technology enhancements (see Cost perspectives).

Different factors affect DAC costs. Those can be divided into capital costs (for process equipment, construction, utilities, etc.) and operational costs (for maintenance, labour, waste removal)[31]. A large share of S-DAC costs is related to the sorbent, whose performances decrease after a number of capture cycles and which needs to be replaced after months to years[2]. L-DAC is more capital-intensive due to its larger-scale, more complex process design, with CAPEX representing almost half of its total cost. Energy prices can also have a significant impact on total costs and are very sensitive to the type of energy used and the considered location. They are expected to vary massively in the near- to mid-term due to changing worldwide energy systems, which adds uncertainty in estimating future DAC costs[5,31].

* First-of-a-kind

Source	Costs ($/t$CO_2$, FOAK)
IEA GHG[23]	400-700
Ozkan et al.[31]	200-600
RMI[32]	500-600
Climeworks	600-800
Fasihi et al.[3]	818-913

Table 2. Estimates of current DAC costs.

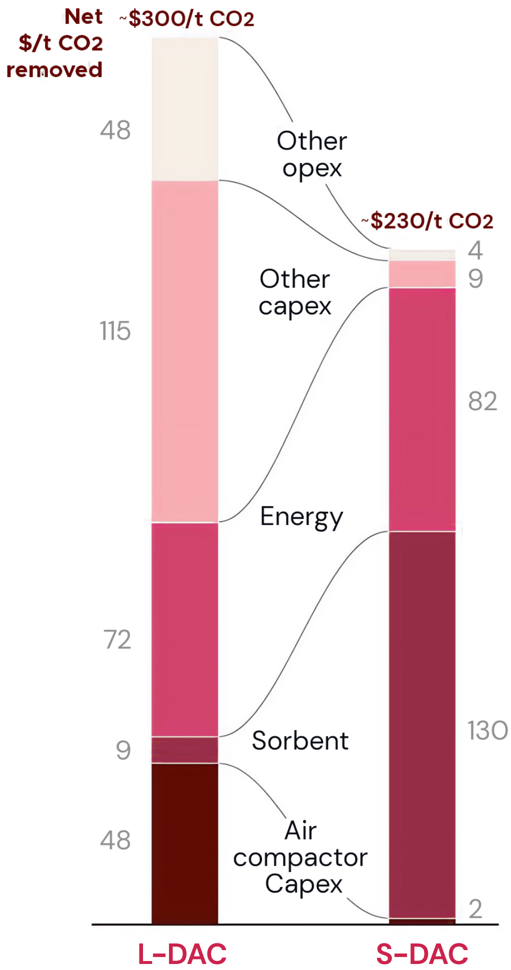


Fig. 4. Breakdown comparison of DAC costs for L-DAC and S-DAC, estimated for a megaton-scale plant. Source: RMI[32].

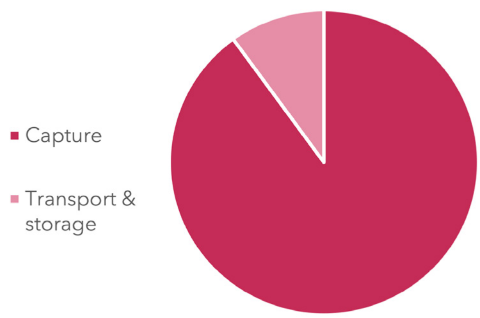


Fig. 5. Compared to other CCUS applications, transport and storage only represent a small share of total DAC costs (ca. 10%), which are largely dominated by the costs of the CO_2 capture step. Adapted from ETC[33].

DAC DEPLOYMENT IN NET ZERO TRAJECTORIES

Which scale is required? Current quantities of CO_2 captured by operating DAC plants are negligible – about 10,000 tCO_2/year, which corresponds to the average annual emissions of 1,000 French citizens[34]. In order to really have an impact on the climate, negative emissions need to be deployed at the multi-gigaton scale by mid-century[11], which represents a massive increase in terms of installed capacity.

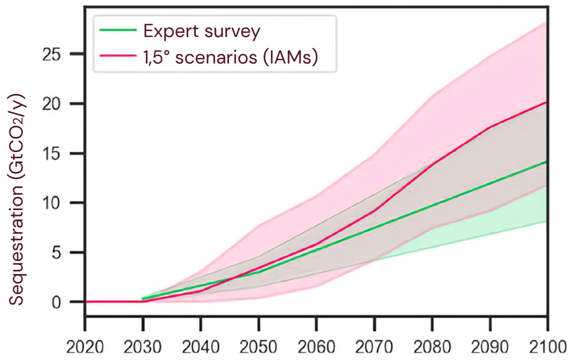


Fig. 6. DACS is not likely to develop at scale before 2030. Median deployment in IAMs and expert estimates tends to reach the gigaton-scale by 2050 in 1.5°C scenarios[35].

The precise role DAC will play in the next decades is still uncertain[27]. To date, no comprehensive assessment of DAC potential has been conducted at global scale. In its latest report, the IPCC retains a median value of 29 $GtCO_2$ captured cumulatively between 2020 and 2100 (with results from studies showing considerable variability, ranging from 0 to 339 $GtCO_2$ captured over that period)[11]. Net zero scenarios developed by several organisations and claims by companies in the DAC industry involve more significant levels of deployment, mostly reaching the gigaton-scale by 2050 and requiring megaton-scale plants to enter in operation during the mid-2020s.

	2030	2035	2040	2045	2050
CarbonCapture	5 Mt				
Climeworks	1 Mt				1 Gt
Heirloom		1 Gt			
Parallel Carbon			2 Gt		
Sustaera			0,5 Gt		

Table 3. Deployment timescales claimed by DAC companies.

BOX 3 | Comparing DAC in net zero scenarios

The **IEA**'s Net Zero Emissions (NZE) scenario[5] does not feature any form of nature-based solutions, relying solely on BECCS and DACS to provide negative emissions. DAC almost reaches the gigaton-scale by 2050, with a cumulative 12 $GtCO_2$ over the 2020-2050 period, requiring massive upscaling (more than 30 megaton-scale plants built each year on average over the period, with a marked acceleration in the 2030s).

The **Energy Transitions Commission (ETC)**[33] considers an evolution similar to the IEA's until 2040, after which considerably larger installation rates are observed (by construction, CDR plays a smaller role in the IEA's scenario). In the ETC's base scenario, DAC captures 3 $GtCO_2$/year (27 $GtCO_2$ cumulatively). The ETC has also developed a 'High development' scenario, in which decarbonisation efforts are not deployed fast enough, thus relying on more DAC being installed (4.5 $GtCO_2$/year by 2050).

The **RMI**[36] considers several deployment scenarios, which range between 700 $MtCO_2$ and more than 5.5 $GtCO_2$ captured per year by 2050.

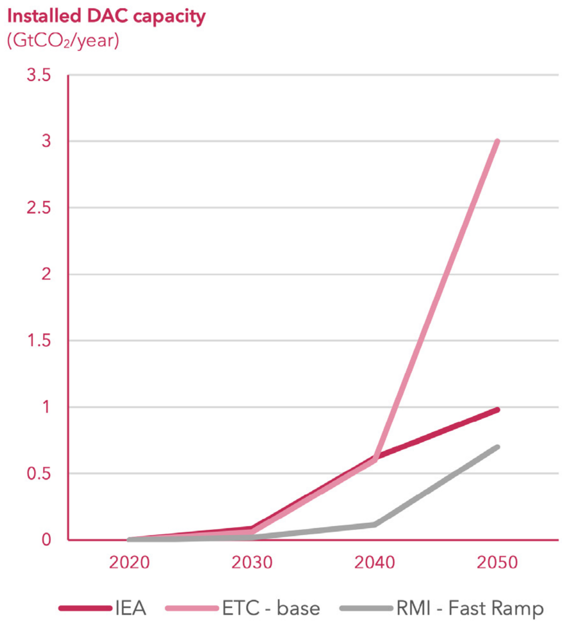


Fig. 7. DAC deployment in selected net zero scenarios.

UPSCALING DAC

Deploying DAC sustainably at significant scales will be challenging. Ensuring the environmental integrity of DAC is crucial and will call for generalized LCAs to make sure projects are truly carbon-efficient and do not lead to undesired damage (pollution, resource depletion…)[18]. Social aspects should also be thoroughly considered[6,18]. Notably, DAC deployment should not enter in conflict with other vital uses of water or energy (especially in a world that is still struggling to transition to low-carbon energy systems[37]) and should be done in ways that permit inclusive engagement of local communities, ensuring fair governance[38].

Consequently, DAC deployment will likely be limited to specific contexts. Energy requirements make DAC only relevant in regions that have already decarbonized their energy mix or that show significant potential for low-carbon energy production[5,39]. DAC is likely not suitable in regions facing water scarcity or harsh weather conditions (temperature, moisture and winds can affect DAC performances[8]), also further impacted by climate change. Various factors may also affect siting considerations: availability of geological storage, industry clusters, geopolitical context, etc.

DAC upscaling requires building a whole industry sector and dedicated market. This includes scaling-up material supply chains (sorbents, solvents and other feedstocks)[6] as well as building the necessary transport and storage infrastructures. Developing appropriate and viable business models is also a central question both for DACU and DACS, that can partly rely on the already existing carbon markets and mechanisms[5,18].

DAC should be considered within the diversity of available CDR and mitigation options. In a majority of scenarios, DAC is only complementary to other forms of CDR, and secondary to drastic reductions in CO_2 emissions: overreliance on DAC in mitigation strategies may lead to dangerous temperature overshoots if DAC fails to reach the expected scale[40], which is usually designated as a 'moral hazard' or 'mitigation deterrence'[41]. Thus, comprehensively assessing and updating the role and potential of DAC within the diversity of climate strategies will need to be done on a regular basis as the technology scales up.

BOX 4 | Policy action to scale-up DAC[18,42]

Current public policies fostering DAC are rather scarce, yet a solid regulatory framework will be necessary to ensure sustainable DAC deployment. Effective regulation can rely on a variety of policy instruments, most of which have already proven successful in the deployment of renewable energies in the past:

- Government support for RD&D
- Government procurement, which can assure the stability of a market for new products
- Tax incentives (in favour of high-permanence removals)
- Regulated standards and norms (LCAs, techno-economic analyses (TEAs), inclusion in international GHG accounting standards)
- High carbon prices, which would make investing in DAC carbon credits a more attractive strategy for customers

BOX 5 | Upscaling DACU and DACS

In most DAC plants currently in operation, the captured CO_2 is dedicated to reutilisation (in beverages or greenhouses for instance)[5,18]. DACU may represent an interesting opportunity to stimulate market creation by providing economic incentives for DAC development. Most scenarios agree that DACS will have a predominant role to play in the future, especially with lowering DAC costs[33]. In the IEA's NZE scenario for instance, by 2050, more than 60% of DAC-captured CO_2 ends up being stored[5].

Large-scale DACS deployment depends on the availability of geological storage facilities. Although global storage capacities are generally thought to be very large (more than 10,000 $GtCO_2$[33]), the actual exploitable potential still needs to be precisely assessed. Establishing strong regulatory frameworks to ensure low-risk deployment of high-quality facilities will be challenging, and the speed at which this can be done may represent a serious bottleneck[18,27].

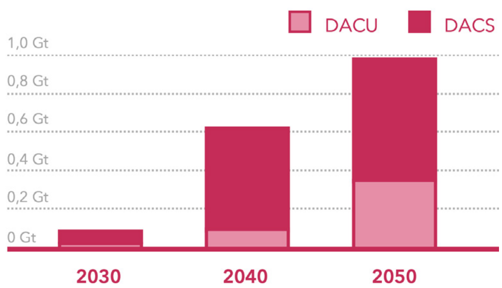


Fig. 8. Global CO2 capture by DACU and DACS in the IEA's Net Zero Scenario, 2020-2050. Source: IEA[5].

TECHNOLOGY PERSPECTIVES

In the coming years, current DAC technologies will continue to benefit from learning by doing, continued R&D efforts and spill-overs from other sectors (point-source capture technologies, electrochemistry, etc.)[5]. Improving materials and optimising processes have been identified as the two main technical challenges[2]. A lot of research has also focused on alternative, less-mature technologies, which present some interesting possibilities. Such technological evolutions will be key in improving the capture capacity, energy-carbon efficiency, and economic viability of DAC.

AXIS 1: IMPROVE CURRENT TECHNOLOGIES

L-DAC | Since regeneration is the most energy-intensive part in L-DAC processes[12], developing novel solvents that require lower regeneration temperatures could enable L-DAC to run on low-carbon energy sources (renewables, nuclear), most of which are already mature today. Another relevant option being considered is to develop new pathways to regenerate the solvent, for instance by relying on electric high-temperature resistance heating or on electrochemical pathways (CO_2 can be liberated from the solvent via bipolar membrane electrodialysis, currently very expensive).

S-DAC | Research on S-DAC is also very active, especially on developing novel sorbents with optimised properties (higher CO_2 uptake, lower heat of desorption, longer lifetime, higher CO_2 selectivity[2]), possibly low-cost, and with limited resource requirements (notably in terms of energy and feedstocks required for manufacture). Current S-DAC designs use a fixed bed, which requires the capture process to be interrupted to regenerate the sorbent – designs with moving beds, although mechanically more complex, have been suggested to overcome this hurdle and enable continuous capture[18].

Systems architecture | Further enhancements in the design of DAC units are also being investigated. Passive DAC systems (TRL 3-5) that do not use fans to collect air have been proposed as a means to lower energy needs, either through designs that rely on natural wind, or by using existing infrastructures that already generate an air flow (such as dry cooling towers or solar updraft towers)[29]. Several actors are also focusing on fostering DAC modularity, which can be a powerful accelerator in deploying a technology (as observed for solar PV or air conditioners in the past), and could be relevant for DAC as well, especially for S-DAC, more modular by nature.

Novel solvents	Aqueous amine solvents, aqueous amino acids, ionic liquids
Novel sorbents	Metal-organic frameworks, zeolites

Table 4. Examples of solvents/sorbents currently investigated[18,43].

AXIS 2: DEVELOP ALTERNATIVE TECHNOLOGIES

A number of research groups and companies focus on developing novel technologies that depart from current solvent/solvent-based approaches. Some of them have already been substantially investigated for point-source capture, a challenge being to make them work at the low CO_2 concentrations required for DAC.

Technology	TRL
Solid-oxide fuel cell (SOFC) DAC[44] High-grade heat from a SOFC is utilised to calcine a carbonate material, removing CO_2 from the air, while also producing electricity. Example of compagnie: ORIGEN	2-5
Electro-swing adsorption (ESA) DAC[45] Based on an electrochemical cell that can adsorb and release CO_2 depending on the applied charge. Compact, obviating the need for high temperatures of pressures, those still need to be demonstrated at low CO_2 concentrations. Example of compagnie: Mission Zero, Verdox	2-4
Membrane-based DAC[46] Already at advanced levels for point-source capture (TRL 4-6), gas separating membranes require high pressure inlet stream and sweeping large volumes of gas, which makes its application for DAC more challenging.	2-3
Cryogenic DAC	X
Microalgae	X

Table 5. A selection of alternative DAC technologies[18].

COST PERSPECTIVES

DAC costs are expected to decrease over the next decades. Most actors in the DAC industry target capture costs of around $100-200/tCO2 by 2050, hoping that the technology will become more and more competitive as it deploys at larger scales. Given the already broad range of estimates for current costs[11], it is particularly difficult to estimate their evolution over the next 30 years, yet some key underlying patterns are worth being analysed.

Several innovation mechanisms might contribute to lower DAC costs, as highlighted by the IEA[5] :

- Economies of scale might be observed with the first megaton-scale plants planned to be built in the next few years. Those may in play in favour of both current technology types: L-DAC systems are large by nature, while S-DAC units, more modular, can benefit from mass production.

- Efforts in R&D, as detailed previously, will improve overall capture performance, thus also contributing to driving costs down.

- Knowledge transfers (technology spill-overs) from other research fields, notably point-source capture, have already been observed in the past and are very likely to continue benefiting DAC, although they are more difficult to predict and quantify.

- Learning-by-doing is a further powerful driver of decreases in costs: as the DAC industry will grow in a larger diversity of scales and contexts, experience will accumulate[31,47]. Learning-by-doing is expected to mainly affect CAPEX costs (OPEX costs depend mostly on external factors, such as energy or materials prices)[2], which could be reduced by a factor 3 to 10 according to the IEA[5]. Several assumptions can be found regarding values for a plausible learning rate, mostly ranging between 10% and 15%. Due to its modular nature, S-DAC is generally assumed to experience slightly higher learning rates than L-DAC (without reaching the very high values observed for solar PV, around 25-30%)[3,5].

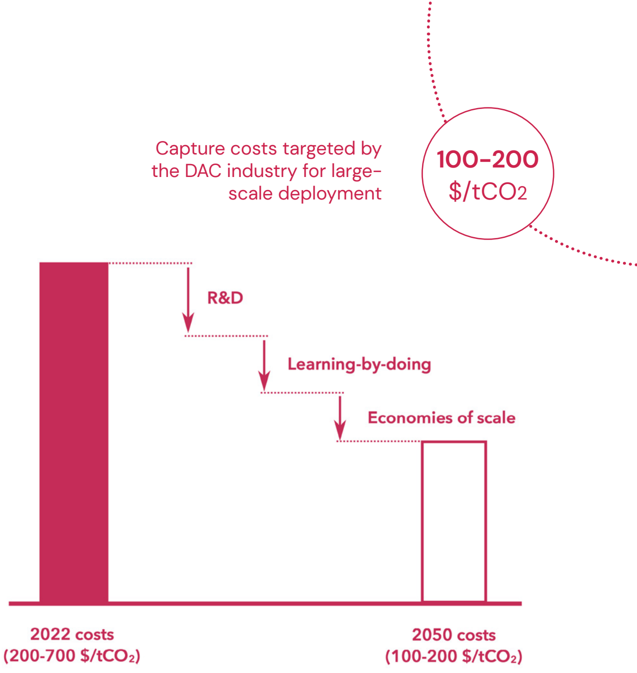


Fig. 9. Potential contributions of different innovation levers for DAC costs reductions by 2050. Adapted from IEA[5].

Estimates for the year 2050 found in the literature are summarised in Table 6 - most analyses find costs that range between $100-200/tCO2. Over the coming years, increased transparency and data quality will be required to be able to adequately follow the evolution of the technology and refine costs estimates[2,48].

Source	Costs by 2050 ($/tCO2)	Learning rate (assumed)
IEA[5]	40-160	8-12%
ETC[33]	70-210	10-15%
RMI[36]	110-340	8-12%
Fasihi et al.[3]	90-200	10-15%
McQueen et al.[2]	100-200	10-20%
Global CCS Institute[49]	137-412	X

Table 6. Estimates of future DAC costs and learning rates.

THE FUTURE OF DAC

As a climate solution, DAC presents a number of key advantages: accountable and permanent CO_2 storage, possibility to provide feedstock for CO_2 use, siting flexibility, low resource requirements, etc. In a constrained context where low-carbon energy demand will be booming for all uses, overcoming the currently high energy needs and economic costs of this technology as well as assessing its potential side-effects will be crucial before it can be deployed at large scale. A number of technological innovations are expected in the next few years that may contribute to improving the energy and carbon efficiencies of current and developing technologies. It is important to remember that DAC remains only one of many CDR possibilities, which remain secondary to drastic reductions in emissions, the utmost priority of climate action.

PRIORITIES FOR DAC DEPLOYMENT

1 Support RD&D

- Key research topics: novel sorbents/solvents, energy reduction via processes optimisation, alternative technologies, novel designs/architectures
- Private and public R&D have a role to play

2 Assess the potential and impacts of DAC in net zero strategies

- Conduct more systemic analyses of DAC potential that encompass a variety of contexts and parameters (energy, water, materials, geological storage, land use...)
- Improve understanding of the role of DAC relatively to other solutions

3 Establish key standards for the DAC industry

- Develop unified LCA and techno-economic analysis (TEA) approaches
- Develop robust and transparent certification methodologies

4 Create a strong political, institutional, and societal framework

- Enhance understanding and framing of governance issues
- Develop communication on DAC, work on local acceptance

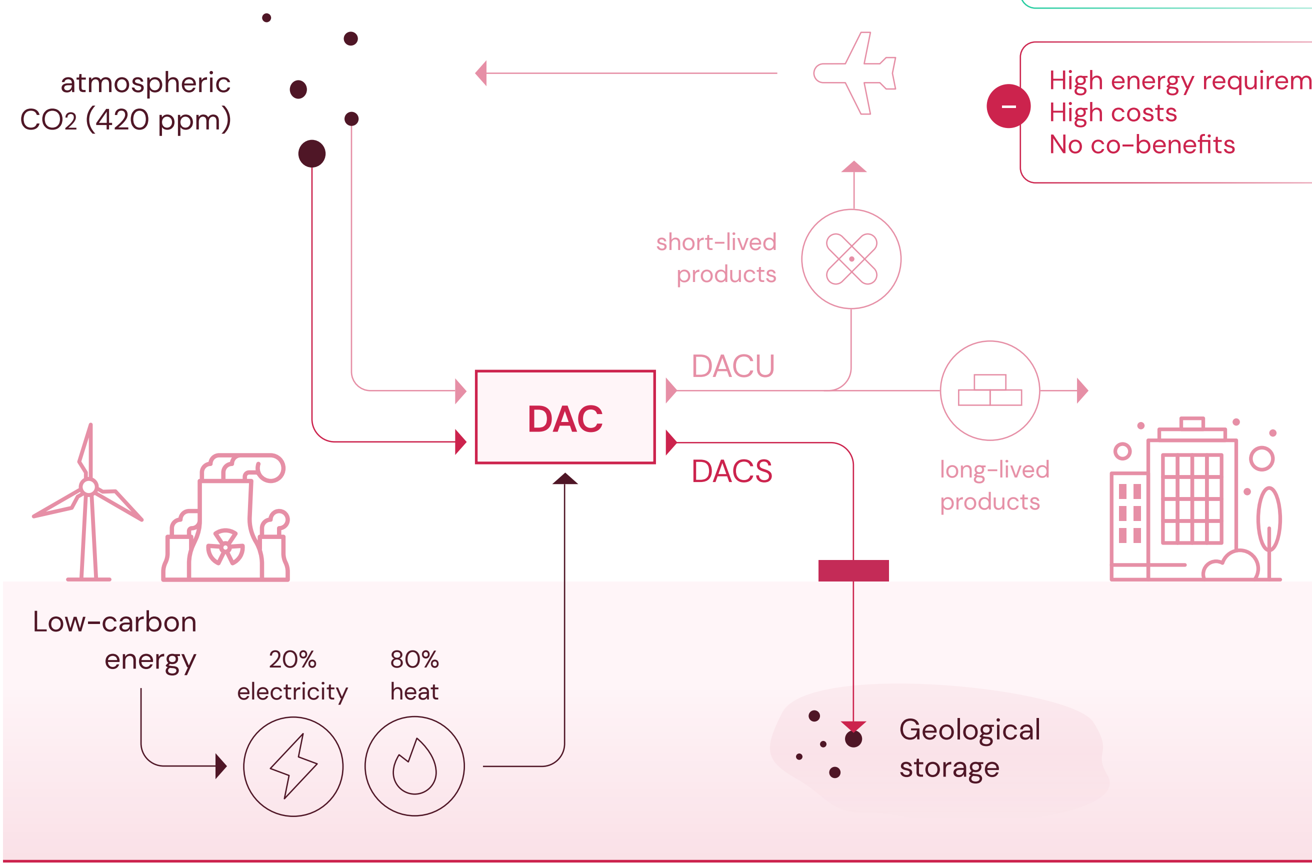
5 Increase financial support to DAC initiatives

- Target promising projects through public and private finance
- Develop favourable financing frameworks (tax incentives, government procurement, carbon prices etc.), especially for early-stage technologies.

A VISUAL SUMMARY | Direct air capture (DAC)

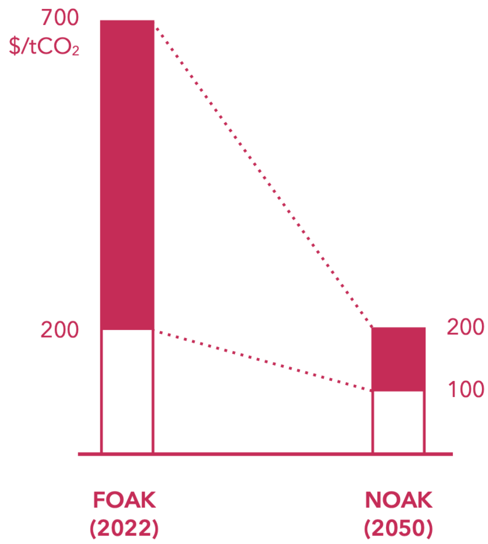
+
- High permanence (DACS)
- Easy CO_2 monitoring
- Location flexibility
- CO_2 feedstock (DACU)

−
- High energy requirements
- High costs
- No co-benefits

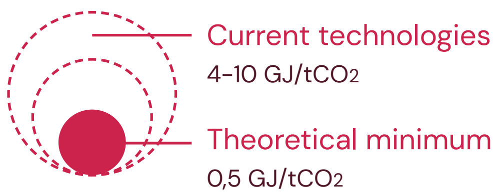


TRL

- **7** Sorbent-based DAC
- **6** Solvent-based DAC
- **2-5** Alternative technologies & design



- 1-6 tH_2O/tCO_2
- 1-60 $km^2/MtCO_2$
- steel, plastics, chemicals
- 75-95% removal efficiency



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