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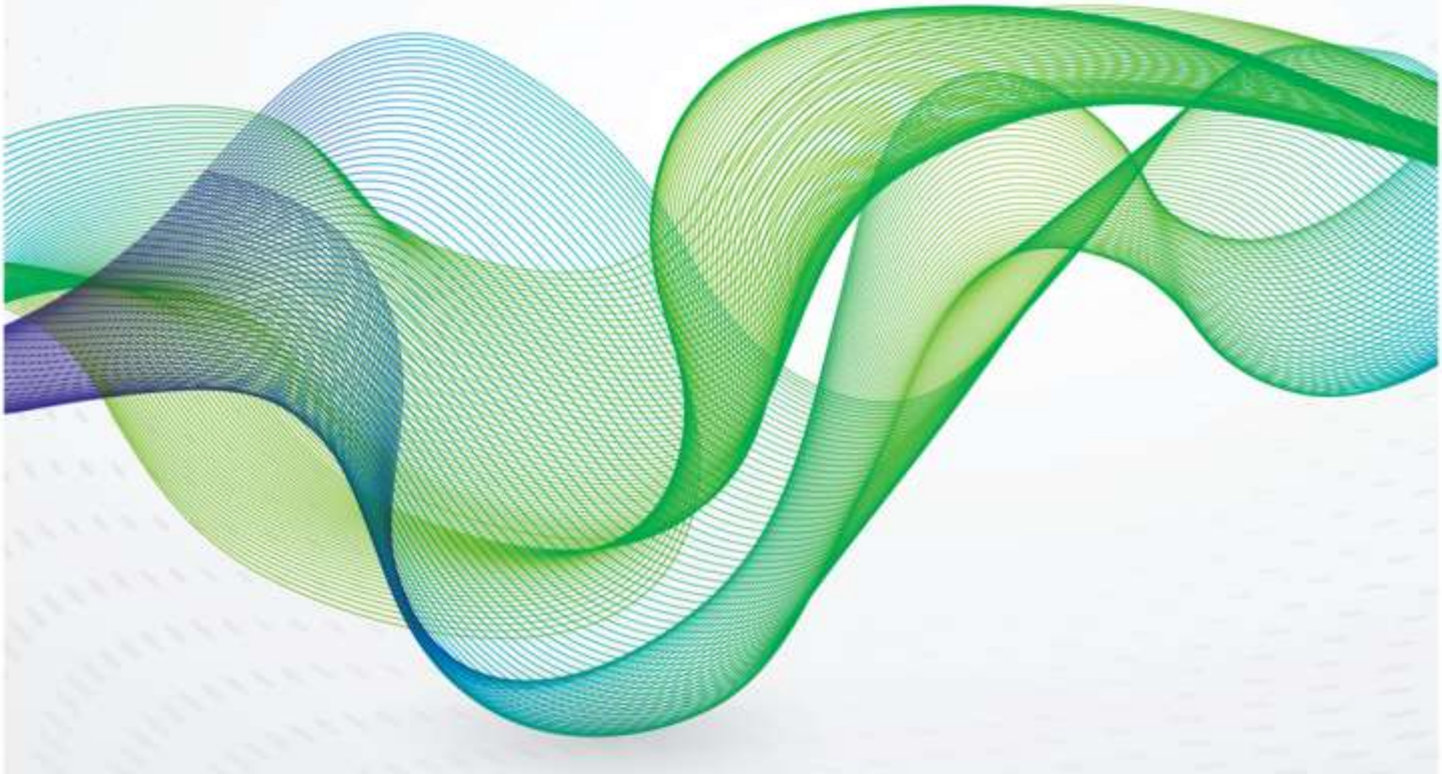
Scaling Direct Air Capture (DAC):

A moonshot or the sky's the limit?



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1. Introduction

In line with the Paris Agreement target, climate action is focused on trying to limit global warming to a 1.5°C increase above pre-industrial levels, with little or low overshoot above that level. Carbon dioxide removals (CDR) – activities that physically remove CO_2 from the atmosphere and store it away permanently – feature in all scenarios consistent with this target, especially given CDR's key role in decarbonising hard-to-abate sectors such as steel, cement, aviation and shipping. Yet, due to increased economic activity and the current policy landscape, overshoot beyond 1.5°C is also worth preparation, with several scenarios including by the International Energy Agency (IEA) showing temperature overshoots.

Direct Air Capture ('DAC') technology coupled with geological Carbon Storage ('DACS', also 'DACCS') has recently emerged as one of the main CDR options alongside bioenergy energy with carbon capture and storage (BECCS), and Nature Based Solutions (NBS) such as afforestation and reforestation. If deployed at scale, these removal solutions would result in 'negative emissions' which would preclude the need for riskier options to abate emissions, such as geo-engineering solutions. In this context, DAC/DACS need to be adopted in addition to existing decarbonisation efforts, including carbon capture and storage (CCS) from point sources. DAC may also be used to generate CO_2 feedstock for applications that have not yet become commercial at scale, including in chemicals, building materials, and synfuels production. Many believe DACS is a measurable, safe, and secure way to achieve removals.

This paper frames DACS in the context of climate science and scenario analysis (section 2) and examines the technical, geographical and political requirements to scale from its current megatonne level of deployment to the gigatonne level needed to achieve the original targets of the Paris Agreement[1]. Section 3 presents the research method adopted, while sections 4 through 8, respectively, discuss the technical, power, geological storage, materials and manufacturing requirements which are needed for the technology to be deployed at scale. Section 9 presents different geographical configurations for deployment, while sections 10 and 11 evaluate costs and policy design to support the technology's adoption. Section 12 concludes.

2. Background

The IEA Announced Policies Scenario (APS), the UN's Inevitable Policy Response (IPR) Forecast Policy Scenario (FPS) and Shell Sky 2050 scenario have atmospheric CO_2 levels exceeding the levels identified by the UNFCCC to be consistent with a low overshoot 1.5°C outcome. These scenario expectations are supported by the observation that, as of end of 2022, annual GHG emissions are relatively stable or increasing slowly at 55Gtpa[2] (of this, CO_2 is 41 Gtpa), while the remaining carbon budget for a 1.5°C scenario is estimated at 380 $GtCO_2$[3].

If current trends continue, this budget is set to expire before the end of the decade. Moreover, consumption and emissions behaviours are not changing fast enough to make that seem less likely. From that point on, climate tipping points are far more likely, according to the IPCC scientific community. To return global warming to 1.5°C above pre-industrial levels, removing CO_2 from the atmosphere at scale will be required. As the level of overshoot in these scenarios is approximately 350Gt, this study asks what it would take – in technical and engineering terms – for DACS to remove that amount of CO_2 from the atmosphere. This should happen in conjunction with deploying CCS at point sources to neutralise emissions which cannot otherwise be abated.

From a technical perspective, DAC can be deployed for two purposes; first, with storage (i.e., DACS) as a carbon removal solution that captures and stores CO_2 in a permanent way, which can assist in decarbonising

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[1] "To meet the Paris Agreement, any potential overshoot above 1.5°C must still remain "well below 2°C". Achieving and sustaining net-zero GHG emissions as per Article 4 of the Agreement will, as a best estimate, lead to long-term declining temperatures, thereby ensuring that temperatures are eventually brought back down below 1.5°C. Paris Agreement-compatible emissions pathways therefore simultaneously keep 1.5°C within reach, limit any potential overshoot to "well below 2°C" with a very likely (90%) chance and achieve net zero GHGs." in a 2023 report by CONSTRAINT, PROVIDE and ESM2025.

[2] Ouworldindata.org annual global greenhouse gas emissions.

[3] According to CarbonBrief.org and the Global Carbon Project (GCP).

hard-to-abate sectors and addressing historical emissions; and second, to produce CO_2 feedstock for synfuels, an option which creates a revenue stream to support deployment but one that also incurs an energy penalty (for synthesis). The risk with deploying DAC to address existing emissions is that, apart from helping to address hard-to-abate emissions, it may be (mis)used to replace existing emission reduction activities, and hence distract from the underlying need to decarbonise. Governments are expected to push hard on underlying decarbonisation.

In this paper, the need to scale DACS is captured and categorised into five key areas which correspond to technical and engineering activities and areas of challenge:

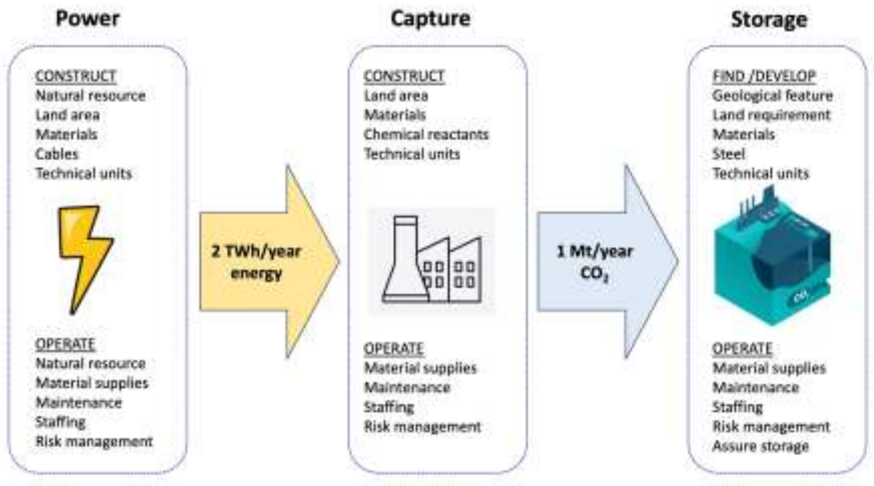
- **CO_2 capture**, i.e., capture of CO_2 from air at scale;
- **Power generation**, i.e., net-zero energy generation to power both capture and storage operations;
- **CO_2 storage**, i.e., transport and permanent storage of CO_2, normally underground;
- **Scale-up**, i.e., resource availability, manufacturing and other potential bottlenecks; and
- **Configuration**, i.e., how to configure different combinations of power, capture and storage.

Following capture itself, the two interdependent engineering challenges are net-zero power generation and capacity for CO_2 storage. These three activities need to be co-located, or at least connected by highly effective power transmission or CO_2 transportation mechanisms.

Current short-term plans seem likely to deliver some multiple of 1Mt of capture capacity before 2030. As such, this analysis is initially based on an assessment of 1Mt ‘units’ of CO_2 capture, including the associated power requirement and storage capability (Figure 1). In the sections that follow, each area (capture, power, storage) is analysed at the scale required to deliver around 1 Mt/year of CO_2 sequestration, which is generally thought to require around 2 terawatt hours[4] (TWh) per year of installed power generation. With respect to power, the focus of this paper is non-fossil and net-zero power; however, we note that current DAC plant plans do include natural gas with CCS as part of their power mix, so that option is briefly reviewed.

In the subsequent sections, the technical aspects of the challenge of scaling DACS from 1Mt to 1Gt by 2050 are assessed. This depends on, amongst other factors, resource availability, land and water availability and manufacturing capability and capacity. The final technical section evaluates configurations and compatibility of the different potential solutions to deliver power, capture and storage in a joined-up way.

Figure 1: Functional units of a future standalone 1Mt DACS system.



Source: Authors’ own illustration with some open-source graphic material.

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[4] IEA and interviews based on public information with technology experts.

3. Research method

The authors undertook three steps to research this paper. First a review of public materials (see references section), second interviews and subsequent Q&A with technology experts, and third discussions and/or review of draft material with subject matter experts. Discussions were restricted to public information and personal opinions. No confidential information was shared.[5]

Questions shared and/or discussed with contributors:

Qualitative:

How would you describe the scalability of DACS technology that you think is most likely to succeed, specifically:

1. *What raw materials (commodities, chemical reactants and rare earth elements) are required for infrastructure construction. Which of these is likely to be in shortest supply?*
2. *What can you say about the day-to-day requirements for the operation of a DACS plant (net-zero energy, water, chemicals, proximity to sequestration location)?*
3. *What can you say about local business environment requirements (staff and technical staff, local amenities and infrastructure, transport and trade links)?*
4. *If starting from the point of a final investment decision, with known plans for an existing plant, what is your estimate of the shortest construction time?*

Quantitative:

Can you estimate the following?

1. *CO_2 sequestration capacity of an example plant built based on existing technology*
2. *Energy requirement of that example plant*
3. *Construction requirements for an appropriate net-zero source of power*
4. *Annual requirements to operate that power plant or network*
5. *Construction requirements for the DACS plant itself*
6. *Operational requirements for DACS plant*
7. *Construction requirements for storage facility*
8. *Annual requirements for storage facility*

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[5] The authors' are very grateful to all contributors for their invaluable feedback, while taking responsibility for any factual inaccuracies or inadvertent misrepresentations in the paper as presented.

4. The engineering challenge

How to capture 1Mtpa of CO_2?

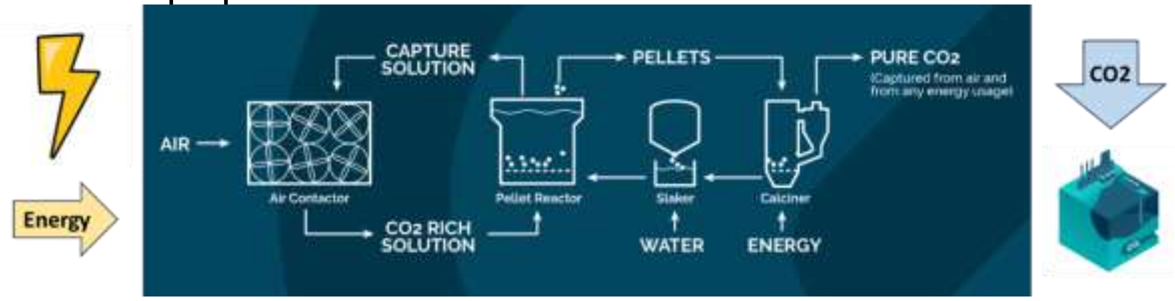
The main engineering challenge at the heart of DACS is to deploy a chemical sorbent which binds onto CO_2 molecules present in the atmosphere, and to then take the chemical sorbent through a cycle which releases a pure stream of CO_2. This is difficult because CO_2 occurs in very low concentrations in the atmosphere, 420ppm or 0.04% by volume. It is much easier to capture CO_2 from relatively high-concentration streams associated with point sources such as fossil fuel power stations or cement factories. The second challenge is to reverse the binding-on reaction in a controlled way. CO_2 can be released from sorbents by taking them through regeneration cycles involving changes in temperature, pressure, voltage, or by bringing them into contact with other chemicals. This creates a pure stream of CO_2, which can then be stored or used.

At present, there are two ways to capture CO_2 from air which are at the point of commercialisation at meaningful scale – in that First of a Kind (FOAK) commercial plants are either operating, under construction, or under advanced stages of planning.[6] These are the Liquid Direct Air Capture (L-DAC), or 'liquid process', and Solid Direct Air Capture (S-DAC), or 'solid process', both of which this paper describes.

4.1 Two types of capture: liquid and solid

Liquid DAC (L-DAC) is based on two closed chemical loops. The first loop takes place in a unit called the air contactor, which brings atmospheric air into contact with an aqueous basic solution (such as potassium hydroxide) that captures CO_2. The second loop releases the captured CO_2 from the solution in a series of units operating at high temperatures (between 300°C and 900°C) (Figure 2).

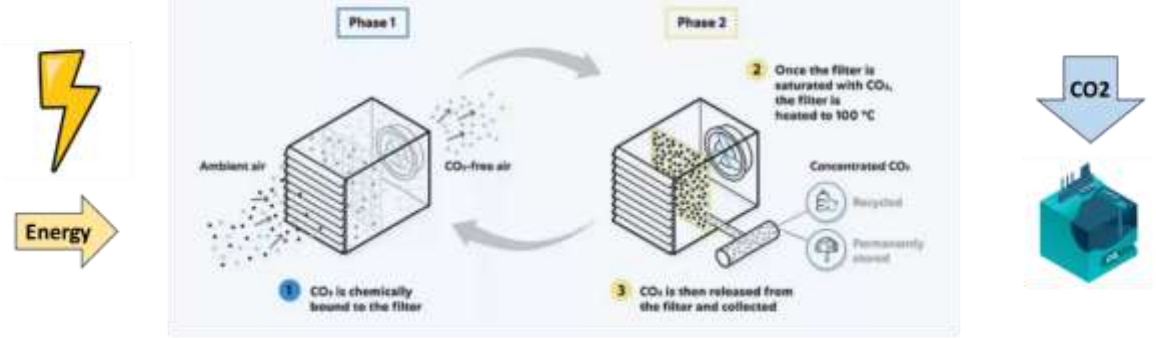
Figure 2: DAC liquid process.



Source: Carbon Engineering.

Solid DAC (S-DAC) is based on solid sorbents operating through an adsorption/desorption cycling process. While the adsorption takes place at ambient temperature and pressure, the desorption occurs through a temperature-vacuum swing process, where CO_2 is released at low pressure and medium temperature (80-120°C). A single adsorption/desorption unit has a capture capacity of several tens of tonnes of CO_2 per year, and there are several units in a capture container (of shipping container size) (Figure 3).

Figure 3: DAC solid process.



Source: Climeworks.

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[6] 'Commercial' corresponds to technical readiness level 7 or 8, the latter being FOAK commercial.

The companies deploying these technologies (developed by companies such as Carbon Engineering, Climeworks, Carbon Capture Inc. and Global Thermostat) are seeking to improve performance through research as well as optimisation. In addition to these, there are multiple[7] other companies working on these same and other technologies in emerging small-scale commercial (e.g., Heirloom)[8] or pre-commercial stages. The technologies electro-swing adsorption (ESA) and membrane-based DAC (mDAC) are examples of this. Any one of these may emerge as the dominant technology and it is difficult to predict which will prevail before commercial rollout at scale, and the development of second-generation plants plays out.

4.2 Capture requirements

Table 1 summarises the key requirements to deliver 1Mtpa of capture capacity. While L-DAC is currently under construction at 0.5Mtpa scale, S-DAC has been operating for some years at ktpa scale.

Table 1: Requirements to capture 1Mt of CO_2 per year.

	Liquid direct air capture	**Solid direct air capture**
Construction		
Land area	100 acres, 40 hectares, or 0.4 km^2	220 acres, 90 hectares, or 0.9 km^2
Location	Not super dry/cold, water, lower altitude preferred	Lower altitude preferred
Materials	50 kt steel, 20 kt cement	40 kt steel, 10 kt aluminium, 20 kt cement
Chemical reactants	10 kt KOH and 20 kt $CaCO_3$	12 kt amine sorbent, up to 20,000m^3 ceramic lattice
Technical units	Various including high-temperature calciner-slaker	Up to 2,000 capture containers with sorbent units
Staffing	Estimated 1,500 full-time equivalents	Estimated 2,000 full-time equivalents
Permitting	Up to 5-7 years	Up to 5-7 years
Build time (excluding permits)	2 years	2 years
Operation		
Water	5 Mt/year, potentially more	0.1 Mt/year, with some potential variability
Heat cycle	900°C, at atmospheric pressure	80-120°C, in a vacuum
Power cycle	Some flexibility; high-temp calciner remains on	Demand response flexibility is possible
Material supplies	Likely not critical	Likely not critical
Chemical reactants	1 kt KOH and 1 kt $CaCO_3$ per year	At least 3 kt amine adsorbent (potential challenge)
Maintenance	Similar to large industrial site with high-temp process	Similar to large industrial site
Staffing	Estimated 100 full-time equivalents	Estimated 100 full-time equivalents
Risk management	Similar to a simple chemical plant	Similar to a large, simple industrial process

Note: these requirements assume a net-zero 2 TWh power source, and where numbers are point estimates, there is a range of uncertainty around each.

Sources: IEA with literature review (Nature, Rhodium, others), interviews based on public information with technology experts.

A geographic location which has access to net-zero power and carbon storage is important. Both technologies have Mtpa equivalent footprints of hundreds of acres and require of the order of 2TWh per

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[7] Examples: Hydrocell, Infinitree, Skytree, Soletair Power, Kawasaki Heavy Industries, Carbon Collect Ltd.

[8] Heirloom recently announced a small-scale (1 ktpa) commercial capture plant in the US using a solid limestone-based sorbent and electric kilns to release CO_2. This may prove to be scalable. As a data point this helps illustrate the range of DAC technologies under development.

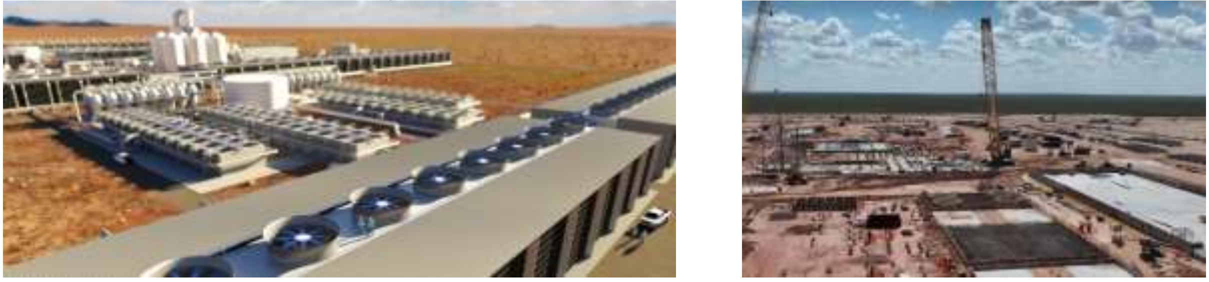
year of power (with a range around that central point estimate). Most of the power required is for the heat cycle to release CO_2 and regenerate the chemical reactants used for the capture process. Standard atmospheric pressures are preferred by both processes, so high altitude locations are less likely to work well.

Construction time for 1Mtpa scale plants is estimated at 2 years. It is important to note that this excludes front-end engineering design (FEED), which can take 12-24 months to complete. The 2-year construction time estimate also excludes permitting, which depends on local and national regulation and policy as well as levels of public acceptance or resistance. Permitting might be quicker with government and public support, and government machinery that works effectively. On the other hand, complex projects and permitting regimes may take years, up to an upper limit of 5-7 years.

4.2.1. L-DAC requirements

The defining feature of the liquid process is that the central regeneration engineering units can be built at large scale, which in turn delivers economies of scale. It follows that a 1Mtpa capture plant needs a reasonably-level 100-acre industrial site (Figure 4).

Figure 4: Left, public source artist impression of an L-DAC plant, and right, recent 2023 photo of the Stratos site in Ector County, Texas.



Sources: Carbon Engineering (left), Occidental (right).

Location: when compared to the solid process, the liquid process requires more water. Around 5 tonnes of water per tonne of CO_2 is required in moderate atmospheric conditions (defined as ambient conditions of 64% relative humidity and 20°C). The liquid process prefers atmospheric conditions that are not very dry nor very cold, where more water is required in dry air.

Construction: Build materials are similar to those required for other similar-sized sites: steel, concrete, and polyvinyl chloride (PVC) are readily available. Chemical sorbents KOH and $CaCO_3$ are required in volume, but these sorbents are simple and available. The liquid process can be scaled on a single site effectively. Central large-scale sorbent and pellet regeneration deliver economies of scale, and ‘design-one, build-many’ modular air contactors can realise economies of scale on the manufacturing side.

Operation: A L-DAC liquid contactor operates continuously with the sorbent flowing through the unit, which means there is a high utilisation rate. The regeneration process requires high temperatures of up to 900°C, which has implications for the net-zero power source. Electric heat does not yet deliver temperatures greater than 500°C in a large-scale, commercial way, except for a few specific iron and steel and aluminium applications (smelting reduction, electric arc furnaces).[9]

Electricity-based calcination is emerging, but currently the concept still needs validation and prototypes need to be built, so this may take a while before it is commercially available for large-scale operation. Natural gas with CCS is the current economic solution for high-temperature heat, which means storage capacity needs to be 30% greater[10] than the direct air capture capacity.

With respect to managing with an intermittent, renewable power supply, the L-DAC process would need to find a way to keep the high-temperature oven hot, while the liquid circuit could be switched on/off fairly

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[9] IEA (2022). Direct Air Capture: A Key Technology for Net Zero. Page 35.

[10] Author interviews based on public information with technology experts.

easily, with implications for the mix of chemical reactants required. More $CaCO_3$ gives greater flexibility to work with intermittent power.

Opportunities for L-DAC technical innovation include the following, all of which are active work in progress:

- Process adjustments, which mean less water, or saline water, for the liquid circuit,
- Chemical process that requires less than the current 900°C to release CO_2, and
- Development of electricity-based calcination at 900°C.

4.2.2. S-DAC requirements

The defining feature of the solid process is its modular form. This is partly due to the challenge of constructing large vacuum containers. It follows that a 1Mtpa capture plant deploying modular solid process technology needs numerous capture container modules, with a total land area requirement of around 200 acres, equivalent to up to twice that required by a liquid process site of the same capacity (Figure 5).

Figure 5: Climeworks' illustrative rendering of what a 1Mt facility may look like.

Source: Climeworks.

Location: the solid process, when compared to the liquid process, requires a lower temperature heat cycle, where the heat component of the net-zero power source can be low-grade heat, such as industrial waste heat or geothermal heat which reduces the electrical power requirement. The solid process can also operate in areas where water availability might be constrained. As water molecules bind to many solid sorbents, it seems likely that cool and dry air is preferred, but technology developers seem confident that sorbents can be designed for a wide range of temperatures and humidities. Highly-integrated collector units that are replicated at small scale may mean that large installations can be constructed in hilly or mountainous terrain.

Construction: Build materials are similar to those required for other industrial units: steel, aluminium, PVC, and concrete for installing capture containers on site, all of which are readily available. A significant challenge to installing the solid process at scale is the complexity of the manufacture of the amine sorbents and the lattice structures that support them. Supply chains for solid sorbents at scale do not exist yet.

Operation: Vacuum regeneration process and amine chemical reactants both bring complexity and challenge. The chemical reactants for the solid process are difficult to manufacture at scale, and it is difficult to replace solid sorbent amines due to the way they have to be fixed to the lattice which supports them.

With respect to managing with an intermittent, renewable power supply, while S-DAC cannot switch on/off instantaneously, some level of demand-side response is possible. Current design expectations indicate that S-DAC might get from 100% to 30% capacity[11] in 1 minute, and it would take about 30 minutes to fully shut down a plant as a few pieces of equipment need to be purged and emptied.

The question of maintaining complex lattice structures and replacing degraded sorbent over the plant lifetime is potentially complex. There is also the question of sorbent lattice performance with particles present which might clog the lattice, as would be the case in dust or sandstorms.

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[11] Author interviews based on public information with technology experts.

Amines are potentially hazardous and regulated. This is manageable when they are used in closed systems, for example to remove CO_2 which occurs as an impurity in natural gas or in the capture part of CCS. Deploying amine sorbent in open systems at scale may present new challenges. Furthermore, it may be that disposal of high volumes of degraded sorbent becomes an issue.

In addition to any large-scale deployment applications, S-DAC might be better suited to small scale and/or diverse rollout (though transport and storage of low volumes of captured CO_2 may become the limiting factor). S-DAC may also emerge as the preferred installation in mountainous or rugged terrain (e.g., in Norway[12]) due to its modular nature.

Opportunities for S-DAC technical innovation:

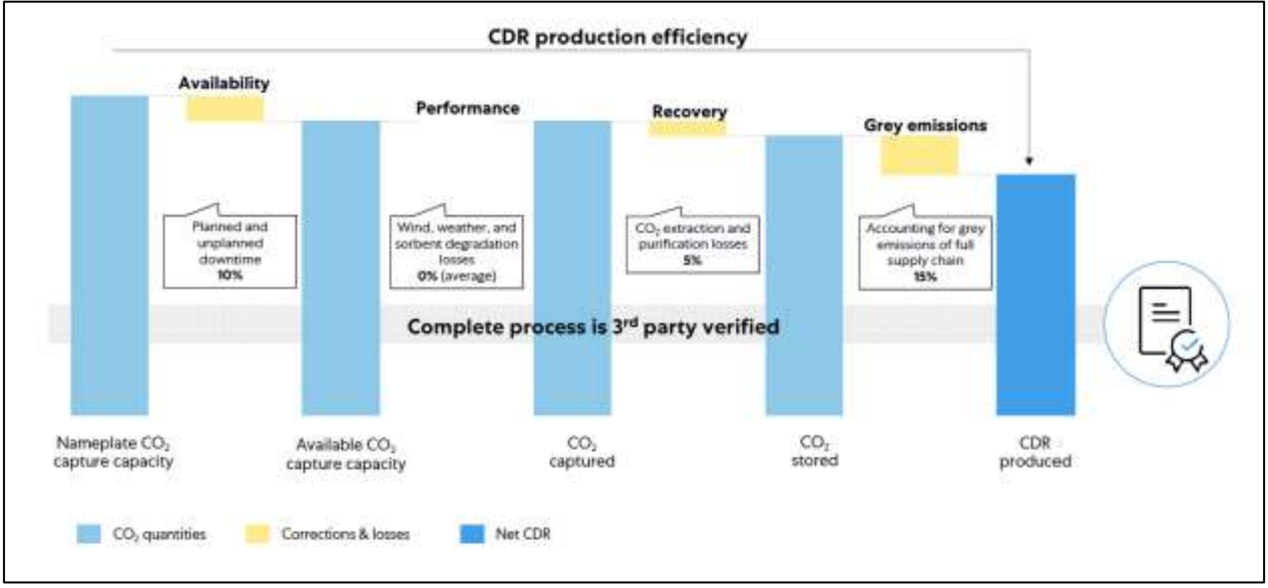
- Solid sorbent amines with longer life and which can be replaced on lattice more easily, and
- Sorbents with a lower regeneration cycle temperature and/or which do not require a vacuum.

4.3 Carbon efficiency

Much like any energy production, extraction or manufacturing process, there are inefficiencies. Plants do not normally run all the time so fall short of nameplate capacity; while capture performance may not run at design levels. There are also ‘grey emissions’ associated with the infrastructure which needs to be built, and the materials and equipment which need to be transported. In today’s supply chains, all these have carbon footprints of their own. The implication is that to adopt this as a high-quality carbon removal solution, these full lifecycle effects must be accounted for.

This study does not attempt to assess the full lifecycle emissions of capture and storage technologies, nor power sources. However, it does acknowledge that full lifecycle carbon efficiency is important, that it should be tracked, and that regulation and assurance steps need to exist so the investor in a removal solution can be assured they are receiving what they pay for (Figure 6).

Figure 6: Illustration of a CDR solution’s carbon efficiency.



Source: Climeworks.

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[12] Bisotti et al. (2023). Direct air capture (DAC) deployment: National context cannot be neglected. *Chemical Engineering Science,* 282, p. 119313.

5. The power challenge

How to power 1Mtpa of CO_2 capture?

One of the implied technical challenges of scaling up DAC is simply to produce sufficient power without emitting carbon. The power required is approximately 2TWh a year to capture and store 1Mt of CO_2,[13] equivalent to the total annual output of a 230MW generation facility with a capacity or load factor of 100%.

Admittedly, no power source runs at nameplate capacity 100% of the time, and some renewables are more cyclical than others. So, there are several ways of delivering 2TWh with different nameplate capacity, and load factors, depending on intermittency of the resource and other considerations which influence their suitability. One point to note is that this study has not analysed options for smoothing intermittent renewable power, which is important for solar or wind. Building on IEA work, this study has estimated the dimensions and assessed interdependencies for a range of renewables, for waste heat, natural gas with carbon capture and storage, and nuclear. Table 2 compares the requirements for generating 2TWh using different power sources, with key messages subsequently highlighted.

Table 2: Requirements for net-zero power generation delivering 2TWh per year.

Requirements for 2 TWhrs/y power generation	Solar	Wind	Hydro	Geothermal	Waste Heat	Gas w/ CCS	Nuclear
Construct							
Nameplate capacity (MW)	1,420	430	500	254	380	285	248
Capacity factor	18%	53%	45%	90%	60%	80%	92%
Inherent cyclicity	Daily, seasonal, weather	Atmospherics, seasonal	Seasonal, climatic	Stable, wellbore dependent	Industrial plant dependent	Stable	Very stable
Natural resource	>3 peak hours	>6m/s average	river with elevation, rainfall	tectonic boundaries	Heavy industry, load factor >= 60%	Natural gas	Uranium
Land area (km^2)	8	64	15	1 (basaltic) 15 (continental)	0.1	2 (including gas gathering)	0.5
Materials	Steel 77 kt, Concrete 69 kt, Glass 53 kt, Plastic 10 kt	Concrete 153 kt, Steel 49 kt, Polymers 49 kt, Glass/carbon composites 8 kt	Concrete 2.6 Mt, Steel 210 kt	Steel, working fluid	build material, generator	Steel, concrete, chromium for gas gathering and power plant.	Steel 2 kt, concrete 6 kt, 45t enriched uranium oxide
Rare Elements	Silver (Ag), Cadmium (Cd), Tellurium (Te), Indium (In), Gallium (Ga), Selenium (Se), Germanium (Ge)	Neodymium (Nd), Dysprosium (Dy)	for standard turbines	n/a	n/a	n/a	n/a
Cables (km)	14	70	n/a	50	n/a	n/a	n/a
Technical units	Inverters, Transformers	Blades, pylons, generators, gears	Dam, intake, generator	Pumps, heat exchangers	Pumps, heat exchangers	well tubing, flowlines, gas processing, compressors, transmission lines, heat exchangers, turbines, generator	Small Modular Reactor (SMR)
Permitting	1-5 years	1-5 years	2-10 years	1-5 years	1-5 years	1-5 years	2-20 years
Build time	18 months	2 years	6 - 10 years	Up to 10 years	2 years	4 years	4 years
Operate							
Material supplies	low level	Spares, lubricants	low level	new well materials,	low level	Gas, spares	Uranium
Maintenance	low, then panel replacement	regular, then replace pylons	testing, bearing replacement	testing, lubes, new wells	testing, lubes, heat exchange	testing, repairs and monitoring	testing and monitoring
Staffing (full-time equivalent)	4	50	50	50	100	50	50
Risk management	Very low risk	Wildlife, blade damage	Dam collapse, variable rainfall patterns	Thermal output, seismicity	Reliant on industrial activity	Loss of containment, public opinion, continued supply	Obtaining consent, Loss of containment

Source: Penspen Analysis.

Note: where point estimates are given, there is a range of uncertainty around that point. See Annex B for details behind the information in this table.

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[13] Some current plants are likely operating above this level but expect to attain 2TWh/Mt in the future.

Key points on power sources:

- Each power type has a different characteristic capacity or load factor, which means that equivalent nameplate capacities to deliver 2TWh/year do vary depending on the level of intermittency.
- Intermittency can present challenges for some DAC processes. For example, the L-DAC process would need to keep the high-temperature calciner hot.
- Land area requirement for some of these options is extensive, which means land availability and alternate use may be a critical factor for siting some net-zero power options.
- Land requirement has different local impact depending on power type and current use. For example, the solar requirement can be extensive, and that land can be used for little else. On the other hand, land between wind turbines or geothermal wellheads may be usable for purposes such as agricultural activities.
- Neither solar nor wind, due to intermittency, are likely to provide an optimal net-zero power solution alone. A combination with some smoothing technology (e.g., battery) is more likely to be successful.
- Rare earth elements are required for solar, though these are not expected to present an undue challenge to delivering solar for DAC at scale (see later section).
- Hydropower is a good stable source of net-zero power but requires particular geography (hills or mountains), and water (either rainfall or drainage from upstream). Build time is also substantial.
- Geothermal is a good option for S-DAC with its lower-grade heat requirement. With the aid of exchangers, heat in the range of 60-120°C would work well.
- Waste heat (industrial) is efficient, but rarely available at the scale required, and the DAC plant would be reliant on the industry in question remaining operational for decades to come.
- Natural gas with Carbon Capture and Storage (CCS) is the net-zero power source chosen by Oxy-1PointFive with Carbon Engineering for their 0.5Mt Stratos project because efficient high-temperature electric heat does not yet exist at commercial scale. This means that CO_2 from the gas burn needs to be stored in addition to the CO_2 captured with the liquid process. Storage capacity in this case needs to be approximately +30% more than capture capacity.
- Nuclear is an effective source of stable power with a small footprint. Small modular reactors (which operate at safer lower pressures) are of the right size to power 1Mt of DAC capacity.
- On the other hand: permitting, and public acceptance of nuclear can be a challenge, and, from a geographic perspective, areas of seismicity need to be avoided, with cooling water available.
- Concentrated Solar Power (CSP) has the potential to provide high-temperature heat in a renewable way, though current plants do not yet deliver the necessary 2TWh/year to capture 1 Mtpa of CO_2.

6. The storage challenge

How to store 1Mtpa of CO_2 and/or potentially use some of it?

The principal method of permanently storing a pure stream of CO_2 is to pump it to an underground reservoir at high pressure or in a water solution, where it stays in supercritical phase, or as the solute in the formation fluids. With time it can turn solid through mineralisation (i.e., conversion from CO_2 to another compound such as $CaCO_3$). What actually happens depends on pressure and temperature and the other fluids and minerals present.

Potential storage options are location dependent and have different characteristics. In addition, transporting CO_2 either short or long distances is possible but not optimal. Two transportation options are here characterised: by pipeline or via shipping. Table 3 provides an overview of the requirements to store 1Mt of CO_2 per year for different transport and storage routes, with key takeaways subsequently highlighted.

Table 3: Requirements to transport or store 1Mt CO_2 per year.

Requirements for 1Mt Storage per year	Oil and gas	Saline aquifer	Ultramafic /basaltic	Pipe Transport CO_2 100km	Ship Transport CO2 1000km
Find/develop					
Geological feature	Stratigraphic, residual, solubility	Stratigraphic, residual, solubility, mineralisation	Fracked basalt, with mineralisation	N/A	N/A
Land requirement	Minimal, downhole acreage	Minimal, downhole acreage	Minimal, downhole acreage	40m for work, 10m wayleave	.05 km^2 for liquefaction, storage and jetty
Materials	Carbon steel, nickel, chromium, cement downhole	Carbon steel, nickel, chromium, cement downhole	Carbon steel, nickel, chromium, cement downhole	Steel, zinc and polymers	Steel, and nickel for cryogenic tanks
Technical units	Well-head and monitoring equipment	Drilling, pipe, well-head and monitoring	Drilling, pipe, well-head and monitoring	Compressors, block valves,	Compressors, refrigeration, insulated spherical tanks, pumps.
Permitting & de-risking	4-12 years	4-12 years	4-12 years	2-10 years	2-5 years
Build time (excl permits)	1-5 years	2-5 years	2-5 years	2-3 years	2-5 years
Operate					
Material supplies	Well tubing, drilling materials, power for injection	Well tubing, drilling materials, power for injection	Well tubing, drilling materials, some power for injection	Power for compression,	Power for compression and liquefaction
Maintenance	Testing and measurement	Testing and measurement	Testing and measurement	Surveillance, testing, pigging, ground care	Hull and rotating equipment maintenance
Staffing (full-time equivalent)	10	10	10	20	20
Risk management	Management, seal penetration, well integrity	Management, seal penetration, well integrity	Management, well integrity	Pipe integrity	Loss of CO_2 cargo through collision
Assure storage	Legacy wells represent trap integrity risks	Monitor to assure storage	Monitor to assure storage	N/A	N/A

Source: Penspen Analysis in addition to discussions with technology experts.

Note: where point estimates are given, there is a range of uncertainty around that point. See Annex C for details behind the information in this table.

Key points on transport:

- Pipeline transport of CO_2 is possible but not always straightforward, particularly in populated areas.
- CO_2 pipeline networks exist in the USA and elsewhere, and there are plans for more.
- CO_2 pipelines need to be heavier wall with a higher pressure than typical gas pipelines.
- CO_2 pumping infrastructure is therefore heavier, it must also keep CO_2 dry while in the pipe.
- Shipping may well emerge as a practical way to move CO_2 over distances of 1000km or more in the near term; and potential future CO_2 tanker destinations may include Iceland, Norway and Scotland.

Key points on storage:

- Storage operations have high fixed cost; need to be large (10s of Mt) to realize economies of scale.
- The materials required (steel, plastic, PVC, aluminium) are not in short supply.
- Transport and storage techniques are well understood, and standards to ensure permanent storage exist in some places.
- Subsurface permanent storage at Mt scale is an area of active research, interest and investment.
- Depleted oil and gas reservoirs and deep (> 1mile) saline aquifers are good storage locations.
- Legacy wells drilled into depleted oil and gas beds may present a risk of leakage.

- Basalt and ultramafic formations are good permanent storage locations as CO_2 mineralises with time, sometimes within 1-2 years[14].
- Storage in these basaltic formations requires water (27t of water per ton of CO_2) and fracking.
- Research is underway on the potential use of saline water (not fresh) for CO_2 injection into basalt for subsequent mineralisation.
- The ability of basaltic rocks and peridotites to provide permanent cap structures at Mtpa scale is seen by some as a stretch, and this calls for research and testing.
- Using natural gas with carbon capture for the L-DAC heat requirement increases storage capacity requirement by approximately 30% above the capture capacity of the LDAC plant.
- One key difference between geological storage of CO_2, and oil and gas extraction from sometimes similar geological structures, is the need to ensure that CO_2 stays where it is intended to be. The US Environmental Protection Agency has done extensive work to develop operational checks and standards to achieve this. These can be found on the US EPA website[15].

6.1 CO_2 use in alternative applications

While technology providers and investors in current projects to commercialise DACS are looking at permanent storage – with sale of associated ‘high-quality’ removal credits as the core of their business model, there are other applications for the captured CO_2.

Building materials

CO_2 utilization pathways in concrete building materials may have the capability to remove low Gt-scale CO_2 in the long term.[16] However, cement requires the use of lime (CaO), which is produced by the calcination of limestone in an emissions-intensive process. As such, unless calcination itself is paired with carbon capture and sequestration, it is difficult to see these delivering reductions in CO_2 emissions on a life-cycle basis. And if it were possible, it seems likely to be limited to pre-cast concrete[17] due to its higher level of CO_2 use for curing compared to ready-mix concrete.

Chemicals

CO_2 can be transformed efficiently into a range of chemicals and chemical intermediates, some of which can be used for fertilisers, but the scale of those applications which are economic seems (at least for now) to be too small to have a meaningful impact on climate.

Synfuel

One potential application is to use CO_2 as a feedstock for synthetic fuels, because when combined with H_2 (a second feedstock), these can be combined or synthesized into hydrocarbon chains to produce liquid fuels such as methanol or diesel. The main challenge with this process is that the quantity of energy required to combine CO_2 and H_2 is multiples of the energy required for the DAC process itself. Nevertheless, the Haru Oni (“land of wind”) pre-commercial demonstration plant was commissioned in 2022 by Highly Innovative Fuels (HIF) on the Southern tip of Chile.[18] These are the latitudes of the roaring forties winds. It produces methanol from electrolysed hydrogen and CO_2 captured from the atmosphere. The plant is powered by a single 3.4MW wind turbine and is currently reported to produce up to 600 tons of methanol per year. The DAC technology in question was developed by Global Thermostat.

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[14] According to CO_2 storage technology developer, CarbFix: https://www.carbfix.com/proven

[15] Source: epa.gov Class VI - Wells used for Geologic Sequestration of Carbon Dioxide

[16] Hepburn et al. (2019). The technological and economic prospects for CO_2 utilization and removal. *Nature,* 575, p. 87-97.

[17] Sick et al. (2022). CO_2 Utilization and Market Size Projection for CO_2-treated Construction Materials. Frontiers Climate.

[18] MAN Energy Solutions (2023). The e-fuels revolution at the end of the world. https://www.man-es.com/discover/haru-oni-e-fuels

7. Resources and materials

This section includes a quantitative comparison of land, water and materials required to scale DAC technology from current deployment levels to the level of one thousand 1Mt-equivalent units (i.e. 1Gt) by 2050. The premise of this study is that DAC(S) capacity should be further scaled beyond 2050 up to 2070, from the 1Gt to 5 Gt level. While this does not represent the same multiplier of scale as 1Mt to 1Gt (5 times vs 1000 times), this is a stage where the question of planetary boundaries may come into sharper focus. All the same, this paper assumes that by 2050, if 1Gt of installed capacity exists, then infrastructure, technology and resource requirements will be different and will adapt to materials and resource availability as process learning takes place over the next two or three decades, and that resource and materials markets would adjust to deliver on urgent resource needs should DACS rollout demand that.

7.1 Land and Water

Land availability

For the capture process itself, land requirement at the 1 Gtpa level with today's technologies would be between 400-900 km^2. For perspective, this is smaller than Greater London (1600 km^2), and when dispersed around the globe in one thousand sites, it seems an entirely manageable land requirement from a land availability perspective.

Using the 8 km^2 estimate presented earlier in the study for land requirement of solar power to deliver sufficient power to capture and store 1Mtpa of CO_2, the equivalent total area – in the unlikely scenario that 1Gtpa is powered exclusively by solar, combined with the necessary smoothing mechanisms – would be 8,000 km^2. Again, for perspective, this corresponds to one third of the area of Sardinia, or 0.2% of the land area of the Arabian Peninsula.

While it would be problematic to construct 8,000 km^2 of solar in densely populated areas of the world, or regions with intensive agriculture, it seems reasonable to conclude that land area will not become a constraint in those less populated areas and sunny arid regions where solar farms at that scale could be built. However, such sites may not be best suited to LDAC, which implies transmission costs and losses. This study concludes that in areas of barren or unpopulated land, both capture plant footprint and renewable power footprint should not present a serious problem.

Water availability

The L-DAC liquid process in moderate atmospheric conditions requires 5t water for every ton of CO_2 removed from the atmosphere, most of which is to replace evaporated water in the liquid loop. At the 1Mtpa scale, this equates to 5Mtpa which is equivalent to the total annual catchment of 5 km^2 of land area, with an average global rainfall of 100cm/year. For instance, the national average rainfall in the USA (30" or 76cm) is a little lower than the global average, but this does not change the catchment area considerably. An average drainage basin in the US would need to be 7 km^2 to collect 5Mtpa of water. Of course, actual river drainage basins are far larger than this.

There are some estimates of L-DAC water demand which far exceed this level. The authors have been unable to ascertain the apparent reason for a demand of 50t water for every 1t CO_2 captured (which is one of the data points provided by the IEA). It seems possible this is an estimate for L-DAC operating in hot dry desert conditions[19]. If L-DAC were to be deployed in this way then access to either plentiful fossil water or treated seawater would be necessary, and if this becomes an issue then it is probably more pragmatic to choose a capture site with higher average humidity such as desert coastlines.

A more relevant question would be the requirement for injecting dissolved CO_2 into basalts and peridotites, which is done with water, in contrast to the injection of dry supercritical phase CO_2 into depleted oil and gas reservoirs or saline aquifers. In the case of water-assisted CO_2 injection into subsurface storage, the requirement becomes 27 tonnes per 1 tCO_2. So, for Gt scale CO_2 injection into basalts, 27Gt[20] of water would be required. This would present a challenge, from a water availability perspective, were we to increase

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[19] In the extremely unlikely, and arguably implausible, event that 1Gtpa of L-DAC were deployed in geographic region with this high requirement for water, the total annual water demand would be 50Gtpa. Which by the author's estimation is approximately the same as the volume of water in Lake Tahoe.

[20] 27Gt is equivalent to half the volume of water in Lake Tahoe.

CO_2 capture and storage to scale using this method in Iceland, for example. Nobody, however, has so far suggested that the full Gt of global capture and storage capacity by 2050 should all be built in Iceland.

Materials

Material and rare element supply constraints to capture 1Gt per year by 2050 need to be seen within the context of demand for materials and rare elements as part of the overall decarbonisation of power grids and economies. In a recent study[21], a comprehensive assessment of requirements to decarbonise total electric power demand was conducted. Technologies considered include onshore and offshore wind, conventional solar PV, concentrating solar power (CSP), hydroelectricity, geothermal, nuclear, coal, biomass, and fossil gas, both with and without post-combustion carbon capture. The study excludes upstream materials associated with fuel extraction and excludes downstream infrastructure, such as CO_2 pipelines in the case of CCS facilities.

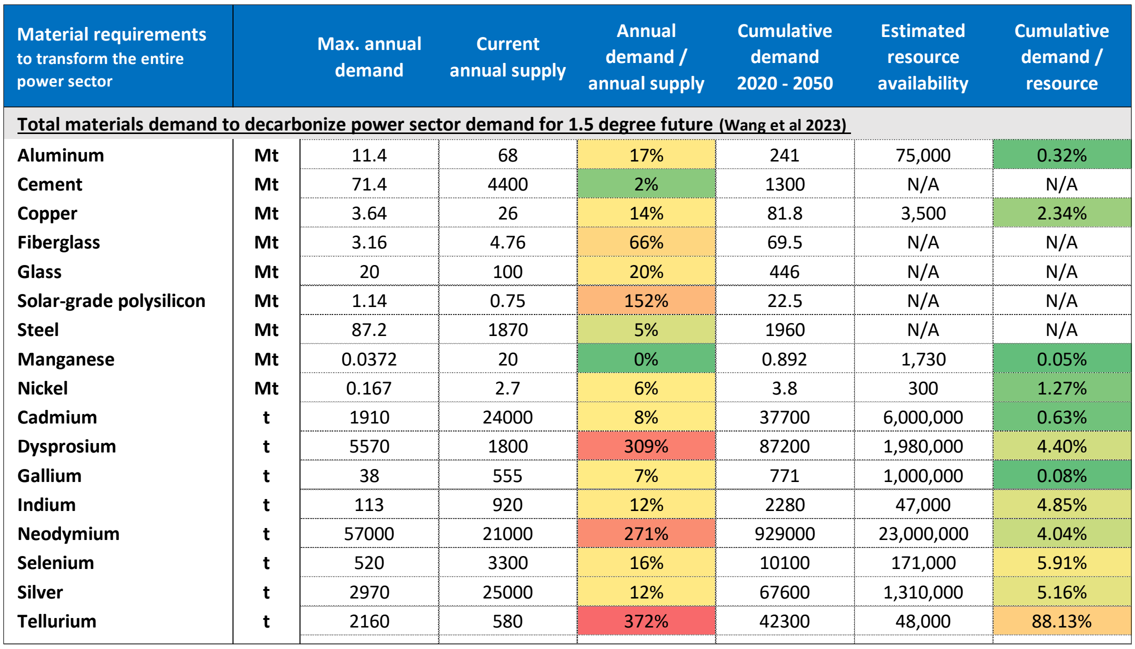
On this basis, they conclude:

- Material production must expand to meet future power generation material need,
- Geologic reserves of materials are sufficient to meet all projected future demand,
- The magnitude of material needs scales directly with wind and solar deployment, and
- Emissions impacts of material production are non-negligible but limited in magnitude.

This paper's assessment, based on numbers presented by Wang et al., (see Table 4), is that:

- Annual production of neodymium (Nd), dysprosium (Dy), tellurium (Te), fiberglass, and solar-grade polysilicon may need to grow considerably.
- Total estimated resource and reserve estimates of tellurium would likely significantly increase if the same effort was put into looking for them as we have done oil and gas.
- Tellurium, which may run in short supply, is specific to thin film solar which is currently just about 5% of the global solar market; and thin film solar is very fungible with polysilicon solar so any tellurium constraint could be mitigated by swapping these technologies.

Table 4: Materials demand.



Material requirements to transform the entire power sector		**Max. annual demand**	**Current annual supply**	**Annual demand / annual supply**	**Cumulative demand 2020 - 2050**	**Estimated resource availability**	**Cumulative demand / resource**
Total materials demand to decarbonize power sector demand for 1.5 degree future **(Wang et al 2023)**							
Aluminum	**Mt**	11.4	68	17%	241	75,000	0.32%
Cement	**Mt**	71.4	4400	2%	1300	N/A	N/A
Copper	**Mt**	3.64	26	14%	81.8	3,500	2.34%
Fiberglass	**Mt**	3.16	4.76	66%	69.5	N/A	N/A
Glass	**Mt**	20	100	20%	446	N/A	N/A
Solar-grade polysilicon	**Mt**	1.14	0.75	152%	22.5	N/A	N/A
Steel	**Mt**	87.2	1870	5%	1960	N/A	N/A
Manganese	**Mt**	0.0372	20	0%	0.892	1,730	0.05%
Nickel	**Mt**	0.167	2.7	6%	3.8	300	1.27%
Cadmium	**t**	1910	24000	8%	37700	6,000,000	0.63%
Dysprosium	**t**	5570	1800	309%	87200	1,980,000	4.40%
Gallium	**t**	38	555	7%	771	1,000,000	0.08%
Indium	**t**	113	920	12%	2280	47,000	4.85%
Neodymium	**t**	57000	21000	271%	929000	23,000,000	4.04%
Selenium	**t**	520	3300	16%	10100	171,000	5.91%
Silver	**t**	2970	25000	12%	67600	1,310,000	5.16%
Tellurium	**t**	2160	580	372%	42300	48,000	88.13%

Source: Wang et al. (2023).

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[21] Wang et al. (2023). Future demand for electricity generation materials under different climate mitigation scenarios. *Joule,* 7(2), 309-332.

7.2 Sorbents

L-DAC Sorbents

(Currently Potassium Hydroxide (KOH) and Calcium Carbonate ($CaCO_3$))

On a global scale, both Potassium Hydroxide and Calcium Carbonate are readily available. To deliver the kind of volumes required for 1Gt of annual DAC, if all are delivered using the liquid L-DAC process, then current market supply would need to increase. There seems to be no reason why this could not happen (Table 5).

Table 5: Sorbent demand.

Material requirements to transform the entire power sector		Max. annual demand	Current annual supply	Annual demand / annual supply	Cumulative demand 2020 - 2050	Estimated resource availability	Cumulative demand / resource
KOH	**Mt**	10	9	104%	267	14900	2%
CaCO3	**Mt**	4503	4500	100%	126043	Very large	0%

Source: Penspen analysis.

S-DAC Sorbents

(Currently amine-based)

While the exact content and structure of amine-based sorbent remains proprietary information, the literature states that the required amine and silica would correspond to 17.4% of the global production of ethanolamine and synthetic amorphous silica[22]. Also, ethanolamine is a precursor of polyethyleneimine that is used as amine for the adsorbent amine on silica. In addition to this, technology developers have indicated that manufacturing supply chains would need to develop to deliver S-DAC deployment at scale.

7.3 Radioactive elements

If nuclear is chosen as a net-zero power source of choice for national power grids as well as large scale DACS, then Uranium supply-demand may become tight before annual production can expand, but global resources are available, and there is the alternative of Thorium, for which there are large estimates of global resource. The expectation would be that over time, the commodity markets and extraction industries would respond to deliver on market demand should it materialise (Table 6).

Table 6: Radioactive elements demand.

Material requirements to transform the entire power sector		Max. annual demand	Current annual supply	Annual demand / annual supply	Cumulative demand 2020 - 2050	Estimated resource availability	Cumulative demand / resource
Uranium	**t**	62306	57700	108%	2479597	6180000	40%
Thorium	**t**	5132	5000	103%	421606	6400000	7%

Source is: Penspen analysis of open access information

Uranium, assumes other demand grows in proportion to power demand to 2050. 100% of DAC power provided
Thorium, assumes other demand grows by a factor of 5 by 2020. 100% of DAC power provided

Source: Penspen analysis.

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[22] Deutz & Bardou (2021). Life-cycle assessment of an industrial direct air capture process based on temperature–vacuum swing adsorption. *Nature Energy*, 6, 203-213.

8. Scaling and manufacture

If DACS scale-up is going to happen to the extent described thus far – over the course of just a few decades, it will require the installation of substantial industrial infrastructure. To describe 1Gtpa scale we offer the following comparisons: 1000 1Mtpa DAC plants with the existing chemical or refining industry; renewable power for 1Gt of DAC with existing global grid power supply; and storage well operations with 1Gt of capacity with existing natural gas infrastructure:

Capture: a 1Mt capture plant is equivalent in size to a small, simple refinery. As there are 825 active oil refineries globally[23], from the capture perspective we would need to build capture infrastructure of the same order of magnitude as the existing refining industry to reach 1Gt of capture capacity by 2050.

Power: to deliver one thousand times the 2TWh of power in a year would require the same level of installed power as 8% of current global supply[24], or just over a quarter of that currently installed in China[25]. One thousand sites are a relatively small number compared to the estimated 62,500 power plants worldwide[26]. However, power production and capture plant efficiency will improve, and some 1.5°C scenarios estimate that installed electricity supply capacity will double by 2050. Furthermore, if efficiency improvements reduce power demand by up to 50%, then 1000-2000 TWh of demand represents 2-4% of the power production capacity foreseen by some 1.5°C scenarios in 2050[27].

Storage: for storage, the closest comparison is the existing natural gas production infrastructure with a total annual capacity of approximately 4000 billion cubic meters a year.[28] This is equivalent to 3Gt of liquefied natural gas (LNG). Therefore, if the difference in gas density is ignored, storage infrastructure required to pump 1Gt of CO_2 underground may be in the same range as one third of the gas extraction infrastructure that exists today.

In summary, and in perhaps overly simplistic headlines, building 1Gt of power, capture and storage infrastructure using today's technology compares to:

- Rolling out a repeat of the existing refining industry, with simpler processes involved,
- Adding 4-8% to total global power generation with net-zero technologies, and
- Building 'reverse' gas extraction capacity one third the size of today's natural gas business.

8.1 Learning from historic precedents

It seems likely that current market, social and political conditions will not precipitate the kind of investment and action required to achieve 1Gt by 2050. However, it may be that climate and social tipping points change the social and political desire and commitment for high-quality carbon removals. If that were the case, then DACS at scale may be the only alternative to risky geoengineering solutions.

There are historic examples where prevailing conditions led to rapid scale-up of manufacturing and technological activity with successful results. Examples include transport ships (manufacturing), covid vaccines (technology) and the space race (technology). Another example is the rollout of refrigerators, however while it did not occur so quickly, nor was it driven by social and political will to the same extent, the technological challenge of using and moving gas in new ways applies to DAC in similar ways as to early refrigeration.

The intent with these comparisons is to identify drivers of success and outcomes that might be relevant to the rapid scale-up of DACS because these themes have a relevance for building policy consensus and investor behaviours. Each comparison is made below, and common themes that emerge are:

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[23] Offshore Technologies (2023). Global top ten active oil refineries.
[24] Statista.com has 2022 world electricity consumption at 25,500 terawatt-hours.
[25] Assumes China's 7600 terawatt-hours in 2020.
[26] According to a GE report cited in Washington Post (2012) All of the world's power plants.
[27] Or between 4-8% of today's installed capacity.
[28] BP (2022). BP statistical review of world energy, 71st edition.

- Collective sense of purpose, recognition of importance or need; be that the survival of allied nations, of a pandemic, of landing on the moon, or people appreciating the value of preserving fresh food.
- Cooperation at the working level around both technological development and the scaling up of the manufacturing process.
- A clear role for governments and international governance structures to prioritise goals, set standards, create incentives and coordinate action.

Transport ships in the second world war

The production of 2700 transport 'Liberty' ships during the World War II in the USA is an example of rapid manufacturing scale-up. These ships played a crucial role in supporting the Allied war effort by transporting troops, equipment, and supplies to various theatres of operation around the world notably across the Atlantic to the UK. The need for them developed because of long and stretched supply chains and severe losses to the merchant fleets of Allied nations. The scale up in manufacturing (like much of the war effort) was a response to the potentially existential threat presented by the war itself.

Success can be attributed to several factors: the U.S. government standardised ship designs, builders adopted assembly line techniques, and focused on mass production. Shipyards specialised in different construction stages, reducing complexity. A skilled and diverse workforce was recruited and trained, apparently working longer hours out of sense of purpose.[29] Efficient material handling and government coordination minimized downtime. Incentives drove innovation. As a result, the U.S. transitioned from producing a few ships monthly to launching an average of three Liberty ships per day.

Covid vaccine development

The production and rollout of several Covid vaccines in 2020 within a year of the emergence of the pandemic itself represented an unprecedented rate of technological innovation. Review studies have identified the following success factors[30]:

- Global scientific cooperation enabled the sharing of research and experimental data which accelerated understanding of the virus and potential vaccines, helped by recent advances in the understanding of mRNA and vaccine platforms.
- Governments and organisations allocated significant funding and resources to expedite research, clinical trials, and manufacturing, and appropriate regulatory agencies streamlined processes without compromising safety, expediting approvals and emergency use authorisations.
- Early investments in manufacturing infrastructure allowed for large-scale production even before vaccine approvals, and international supply chain cooperation ensured the availability of raw materials and distribution networks.
- Finally, there was useful collaboration between governments, pharmaceutical companies, and research institutions to make the most of expertise and resources.

Space race

This was a defining chapter in the 20th century, primarily between the United States and the Soviet Union. It began with the Soviet launch of Sputnik in 1957, marking the first artificial satellite in orbit. This triggered a fierce competition, culminating in the United States' Apollo 11 mission in 1969, when astronauts set foot on the Moon. There were tremendous technological advancements, including the development of spacecraft, rocketry, and satellite technologies. It had significant political and scientific implications, eventually leading to international cooperation in space exploration. Critical success factors included the following:

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[29] Source: "Liberty: The Ships That Won the War" by Peter Elphick.

[30] Solis-Moreira, J. (2021). How did we develop a COVID-19 vaccine so quickly?, and Bok et al. (2021). Accelerated COVID-19 vaccine development: milestones, lessons, and prospects, *Immunity,* 54(8), 1636-1651.

- Unwavering political commitment from the United States and the Soviet Union. The Cold War rivalry fuelled a sense of urgency and competition, leading to substantial investments in space exploration.
- Clear goals and deadlines. The Apollo program had a clear objective: landing a man on the Moon by the end of the decade. This specific goal provided a clear direction and timeline for the program.
- Cost-effective decision-making. While the Apollo program was expensive, its costs were justified by the technological advancements and geopolitical benefits it provided.
- Technological innovation. Development of materials, computer systems, and engineering techniques.
- International collaboration. The space race saw competition between superpowers but also moments of cooperation, such as the Apollo-Soyuz Test Project.
- Public support. The Apollo program enjoyed widespread public support, which translated into funding and government backing. Raising awareness and building public support were essential.
- Long-term vision. The space race and the Apollo program were ambitious undertakings that spanned years; there was a recognition that meaningful change takes time.

Refrigeration from invention to one in every home

Some energy experts interviewed for the purposes of this study have informally compared current DAC technology to the refrigeration technology that was available in the early 20th century when the development of Freon or CFC enabled the widespread adoption of electric refrigerators in the 1930s. While this development was not driven by an existential threat as in the case of DACS, or benefit from the urgent intervention of governments, it does provide an example of similar complex technology (at least for now), albeit over a longer period of time.

Following World War II, advancements in materials and manufacturing techniques reduced costs, making refrigerators more affordable, and the advantages of cold storage for food, drinks, medicines, ice and frozen food were clearly appreciated by populations around the world. The scaling up of refrigeration technology was driven by innovations in compressor design, better insulation materials, and mass production techniques. Increased affordability stemmed from economies of scale, competition among manufacturers, and improved energy efficiency. Government regulations on environmental concerns also played a role in enhancing efficiency and reducing harmful emissions.

In the 1980s it became clear that some CFCs were having an important and harmful effect on the protective ozone layer in the upper atmosphere. Scientific, social and political pressure led to an international agreement, the Montreal Protocol on Substances that Deplete the Ozone Layer in 1987. As a result, steps to phase out harmful CFCs were identified, including the development and adoption of alternative refrigerants.

Today every household that can afford one has a refrigerator. Fridge production runs at 215 million per year[31]. If we produced small DAC appliances like this, and if each captured 5 tonnes CO_2 per year (think mini solid sorbent capture container), then that's equivalent to 1Gtpa of DAC capacity *built* each year. Though note, a small domestic-scale CO_2 disposal method would also be required, and that seems a way off at present. Despite different timelines and sense of urgency, the technological and manufacturing steps of refrigeration do have some similarities with the previous three examples. There are also similarities between the international agreement on CFCs and the existing and ongoing climate process led by the UNFCCC.

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[31] Statista (2023). Refrigerators: statistics & facts. https://www.statista.com/topics/2182/refrigerators-and-freezers/#topicOverview

9. Configuration

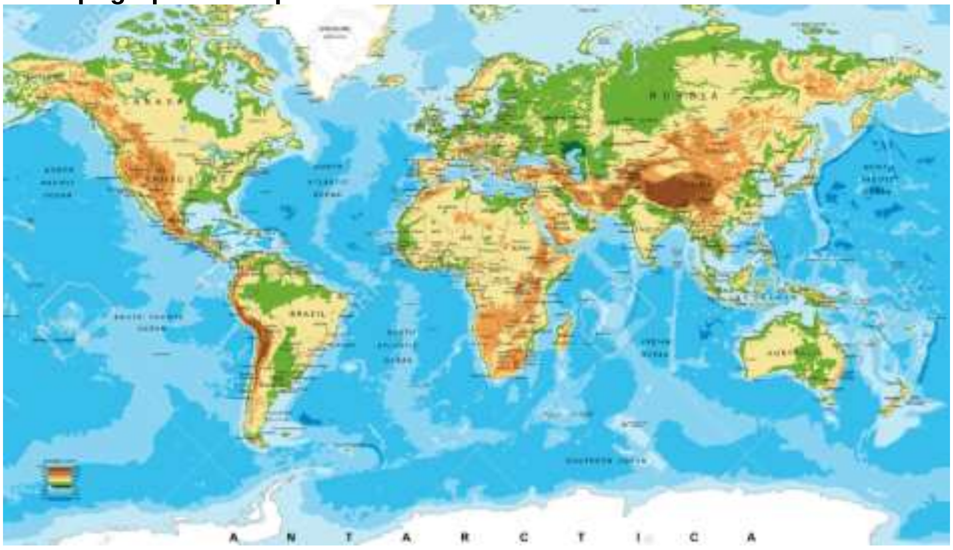
As noted earlier, any large-scale deployment of DAC technology will likely happen for one of two reasons: 1) DAC coupled with storage for carbon removal, or 2) DAC used to provide CO_2 for further utilisation. For the former, in addition to net-zero power and good conditions for DAC, the plant needs to be close to geological storage, or else an installed CO_2 transport infrastructure. For the latter, additional power may be required for fuel synthesis. Here, we unpack some of the details behind location of renewables and geological storage and offer insights on the location of the DAC plant itself.[32]

9.1 Favourable direct air capture operating environments

Atmospheric conditions

DAC tends to work better in dense air, implying lower altitude and cooler air. This means green zones in Figure 7 are preferred, potentially at higher latitudes. That said, some altitude (beige shading) is acceptable.

Figure 7: World topographical map.



Source: Open Source.

Water and humidity

Implementing the liquid process can be challenging in excessively dry air and has higher demand for water from local or distant rainfall or treated seawater. Figure 9 (above) shows the humidity world map with a scale from 0 to 100%, with moderate humidity in light green. For ease of reference, 64% (marked on the key) is the level at which an L-DAC plant uses 5t water per 1t CO_2 captured. Figure 8 (below) shows the precipitation world map credit with a global average rainfall of 1000mm (marked on the key).

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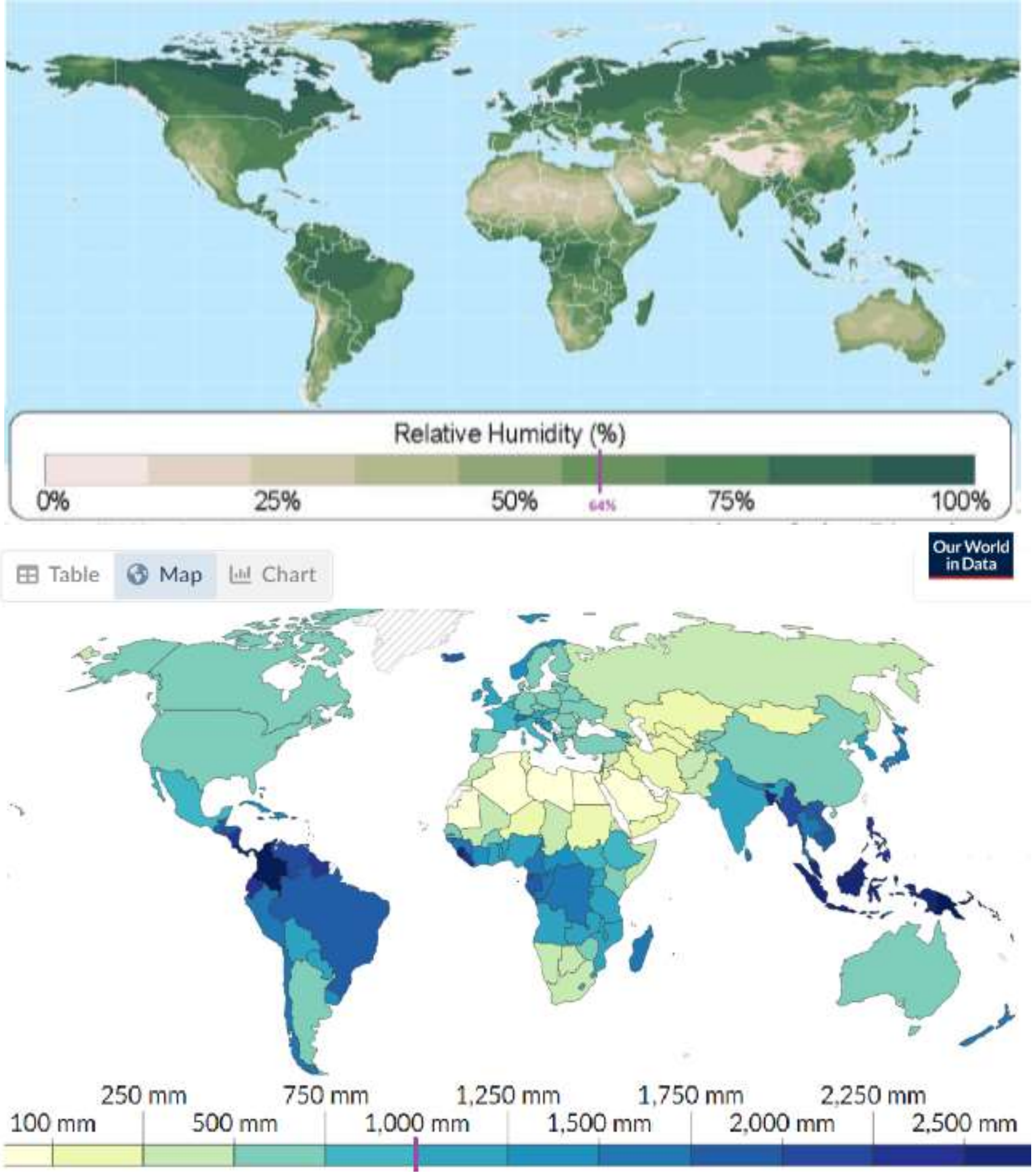
[32] More detail on such geographic considerations is provided in the CDR primer: https://cdrprimer.org/read

Figure 8: Humidity world map (above) and precipitation world map (below).



Sources: Office of Sustainability, University of Wisconsin–Madison (above), Our World in Data (below).

9.2 Proximity to a net-zero power source

Solar and wind

Given the cyclical nature of solar and wind, candidate locations would be coastal locations for wind with plentiful sunshine for solar. In practice the following can be well suited for a combination of solar and wind power:

- Equatorial and subtropical coastal locations with sun, including west coast of North America, South America, Northwest, Southern and Eastern 'Horn of' Africa, Arabia and much of Australia,
- Arid central regions with higher average wind, including in Central North America, Central Argentina, Saharan Africa, Arabian Peninsula and inland China, and
- Some scenarios (e.g. Shell Sky 2050) envision DAC rollout in Mali, Niger, Sudan and Chad, partly due to the potential availability of renewable resources.

Alternative net zero power sources

Geothermal energy may be better suited to the S-DAC process with its lower temperature heat cycle. geothermal potential is higher at tectonic plate boundaries, particularly:

- West coast of the Americas, especially western Canada and Southern Chile,
- Where volcanic islands and countries exist, associated with mid-ocean ridge volcanic activity,
- Active tectonic belt through central Europe from Germany, through Greece to Turkey,
- Southern extent of the Red Sea between Africa and the Arabian Peninsula,
- Volcanic regions of Indonesia, Philippines and from Japan to the Aleutian Islands, and
- New Zealand particularly the north and south coastal regions.

Hydro power depends on high local or upstream rainfall, and sufficiently mountainous terrain to allow the construction of a dam. Best hydro potential seems to be in the mountainous regions of western Canada, Colombia and Chile, central America, the alpine regions in Norway and across central and southern Europe, some locations in western Africa and Ethiopia in the east, the Himalayan mountains and surrounding drainage basins. Note that build time for hydro plants is long.

Waste industrial heat depends on industrial clusters, which rarely generate the continuous 500MW-equivalent level of heat required to power DAC at scale.

Nuclear power can be fairly flexible, though it does require cooling water, and a stable tectonic location, so coastal locations in higher latitudes, away from seismic activity, are preferred.

For maps of different energy sources, see Annex B.

9.3 Proximity to a CO_2 storage location

It is key for any DAC development to be either located at a potential geological storage site, or close enough to pipe CO_2 to the site. Geological storage in depleted oil and gas or saline aquifers are associated with sedimentary deposits (see Annex C for a map). Basalt and ultramafic formations have also been mapped.

9.4 Likely configurations

The characteristics of the key activities and capture technologies described above mean that some configurations emerge as more likely candidates for implementation than others, these include:

- Natural gas with CCS, with L-DAC process (high temperature),
- Waste heat or geothermal, with S-DAC (lower temperature),
- Solar/wind with battery may better suit S-DAC with more operational flexibility,
- Nuclear with either L-DAC or S-DAC, and
- Modular S-DAC deployment for peak shaving of grid, though transport to storage may be an issue.

10. Costs and financing

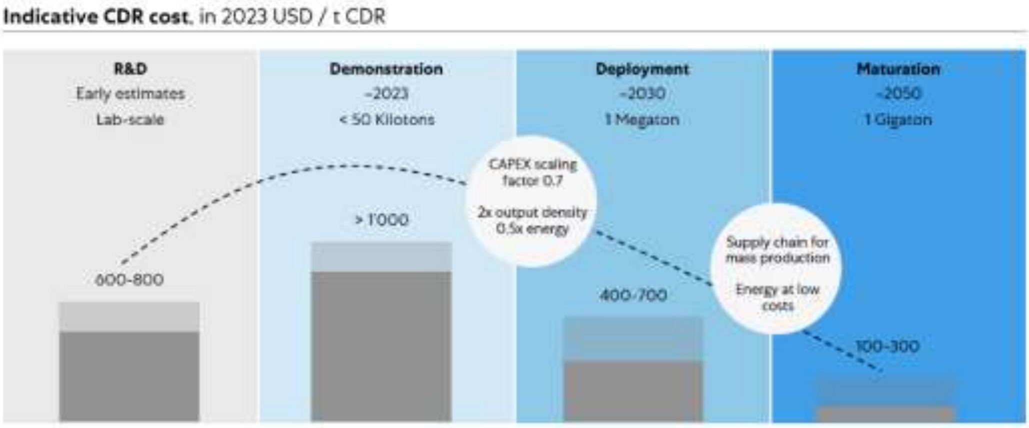
Current pre-subsidy unit costs have, for a while, been estimated in a range around 800-1000 $/tCO_2$. Public transaction information implies this is probably still the case, with a broad range of prices paid between $700 - 1400 per ton[33] of CO_2 removed and stored.

By one measure, the weighted average cost of all DAC removals (including storage) announced in a public way over the last 3 years is 718 $/tCO_2$.[34] This 'market' value seems likely to reflect some level of government subsidy. One recent transaction was the 800 $/tCO_2$ paid[35], in effect, by JP Morgan Chase to Climeworks earlier in 2023. If this benefits from the 180 $/tCO_2$ of IRA support, then it implies the pre-subsidy removal cost for Climeworks removals is still close to the 1000 $/tCO_2$ level. There are lower unit price ranges out there (400-630 $/tCO_2$)[36] but it is difficult to unpack these into component costs. Cost ranges are highly dependent on the power source.

One reason why the cost band is so high is that current projects serve the dual function of 'selling credits' in the voluntary carbon markets and 'testing the technology'. There are other potential reasons for this. First, there are two different technologies (L-DAC and S-DAC) with different inherent costs structures. Second, power costs – both heat and electricity – are different and site dependent. Third, subsidy regimes are different and the extent to which subsidies are reflected in unit removal costs is opaque. Fourth, storage costs vary depending on method (supercritical injection or water-based for mineralization), and whether they are included in the cost build-up or not. It would help investors to understand risk-reward expectations if there were more transparency around unit DACS costs. An agreed methodology would help.

Looking ahead, Climeworks estimates costs could move to 400-700 $/tCO_2$ by 2030 and 100-300 $/tCO_2$ by 2050. This fall in cost is predicated on deployment-led innovation and iterative learning, in particular to improve the chemical process and to realize both heat-cycle and mechanical efficiencies. Figure 9 illustrates this.

Figure 9: Indicative current and future CDR costs



Source: Climeworks.

From a capex perspective, 1PointFive and Carbon Engineering have taken FID on their 0.5Mt Stratos Project with a headline investment of $1bn which is believed to include both power and storage. This gives a sense of the level of investment for a near-term future 1Mt plant.

According to the latest work from the Inevitable Policy Response (IPR)[37], a Mt-scale plant such as Stratos operating at 'full capacity' would cost (pre-subsidy) around $600 per ton of CO_2 removed. It is reasonable to expect this materializes by 2025. IPR expect this cost baseline to come down as next-of-a-kind plants are

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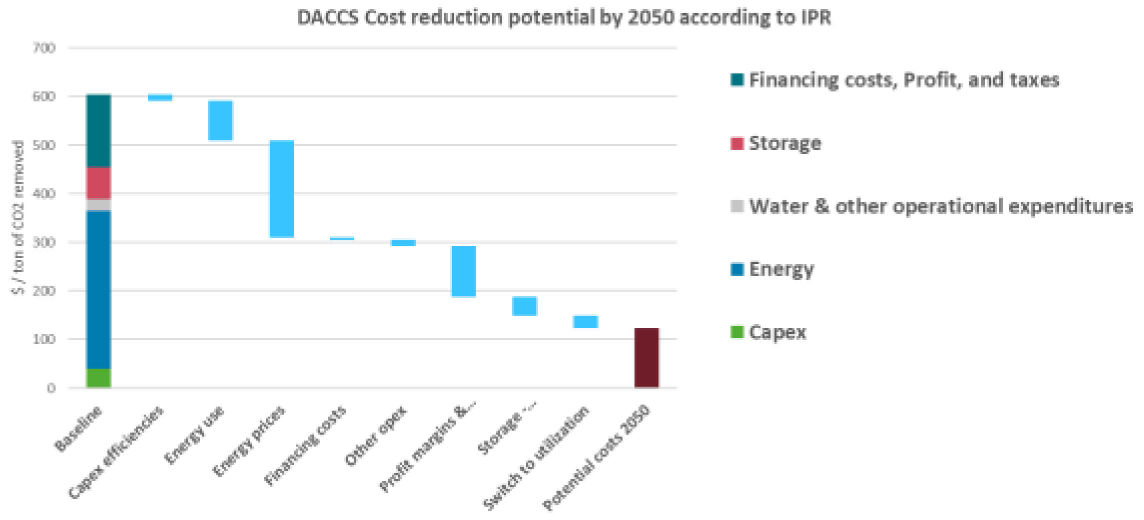
[33] $1400 is the cost of 1000kg of carbon removal on the Climeworks website (November 2023).
[34] Source: cdr.fyi, as of October 2023.
[35] Source: Ramkumar (2023). JPMorgan Chase makes one of the biggest bets ever on carbon removal.
[36] Source: Oxy/Carbon Engineering in their Q2 pack, slide 38.
[37] Inevitable Policy Response (IPR) (2023). Financing Direct Air Carbon Capture and Storage: Quantifying the investment opportunity.

built, economies of scale are realized and process optimization takes place. Key drivers of reductions include the power source, energy efficiency, operating costs, profits, taxes and carbon disposal costs. The potential cost reduction pathway from $600 to $120/tCO$_2$ is illustrated in Figure 10.

Figure 10: 2025 and 2050 carbon removal costs.



Source: Inevitable Policy Response (IPR).

A combination of energy efficiency, further reduction in electricity generation prices, and the switch from retail to 'at cost' electricity use could reduce almost half the costs of DACS today. Related savings may be possible in the use of heat. Storage costs will benefit both from an increase in efficiency as projects scale and may eventually reach zero if CO$_2$ commercial utilization at scale becomes a reality, notably for building materials. There may even be a point where fees could be earned for the sale of CO$_2$ as a commodity, further reducing overall costs. Returns on investment are currently a significant share of costs given the need for a meaningful return rate on a very capital-intensive project. Some estimates suggest that roughly one-third of future costs will be associated with a combination of profit margins, taxes, and financing costs.

One recent development is that Blackrock invested $550m[38] into a joint venture with Occidental to help develop the Stratos project. In doing so, they effectively placed a bet that carbon management will play a significant role in global decarbonisation to the extent that investor returns will be meaningful. The $9tn money manager is making the investment through its fourth global infrastructure fund[39], which focuses on climate-related projects including those that help brown industries become greener. On the other hand, a regulated environment may require different profit margins and allow for different tax regimes, not the least if upfront capital is provided by governments.

Who Pays?

A key question for DACS is who pays for it. Presumably, there is some price point (up to $100/t) where the private sector would be willing to cover the costs of negative emissions, although whether this would cover all residual emissions and/or the requisite need for negative emissions technologies is not clear. As current pilots and prices demonstrate, there are also some market actors willing to pay a higher price.

DACS may become a component of regulated Emissions Trading Systems (ETS). As prices in these systems rise, regulation may allow for paying for removal rather than the emissions certificate (of course, hypothetically, governments could use the proceeds of ETS to pay for removals as well). For the moment, it is clear that the underlying politics and policies of DACS at scale remain unresolved. Ultimately governments will likely have to explore one of three options:

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[38] According to Blackrock and Oxy public announcements, which were widely reported including by the FT. link

[39] In 2022 it raised $4.5bn towards an eventual $8bn goal from global pension funds, insurance companies and sovereign wealth funds.

1) Costs are sufficiently low that voluntary market initiatives can scale. While this appears as an ideal outcome, there is significant uncertainty as to the extent to which companies would – again, at scale – be willing to absorb a ‘voluntary cost’;
2) DACS is integrated into ETS’s in some form, or a similar policy requirement is introduced that functionally serves the same purpose; or
3) Governments pay for DACS directly and finance this through a combination of tax schemes (including potentially ETS) and borrowing.

A simple analysis of government subsidy requirements conducted by IPR suggests scaling to the Gt-scale may require upwards of $2 trillion over the next three decades.

Financial regulation and policy lever

With respect to deploying finance at the scale necessary to enable innovation and process improvement, it is evident that this cannot happen yet because the business model does not work at a price that the current voluntary carbon market (VCM) or CDR market are willing to pay in any great scale, despite the high quality of DACS removal credits. While small-scale investors willing to pay a premium do help (see box), and their purchasing behaviours will likely help with public acceptance – which is important – the scale of investment they bring seems unlikely to pay for the scale of installation required to bring costs down in the way that is needed.

This seems like a good example of where governments could deploy subsidies and other policy instruments to provide the revenue certainty essential for projects to attract greater private investment levels with viable business partners along the value chain. Technology developers themselves believe that unlocking investment will depend on a supportive financial system, which enables investors to make good decisions and execute them in an efficient way. This will also mean that any incentives have maximum impact (see next section on policy design).

> “*Alban Wesly drives an electric car and eats a vegetarian diet in an effort to live a climate-friendly lifestyle. This month, the bassoonist in Amsterdam completed another task on his greener living to-do list: Paying to have carbon dioxide removed from the atmosphere. While corporate buyers and governments are pouring billions into the carbon removal industry, individuals like Wesly have opened their wallet, too. Though the payments are relatively small, startups working on pulling* CO_2 *from the air are using sales to individuals to build support for grander ambitions*” Bloomberg 2023

Climeworks, for example, identifies the following priorities: standards for rigorous CDR monitoring for assurance, reporting and verification to ensure permanence, measurability, verifiability, net-negativity, additionality, and social and environmental co-benefits. Building on this, they believe that a CDR market must be developed at scale. Direct public procurement and compliance markets such as the ETS could help create and secure large-scale carbon removal markets.

11. Policy design

As noted earlier, DACS can be deployed as a carbon removal solution, or to produce CO_2 for further utilisation. The risk with deploying DACS to address existing emissions is that, like any negative emissions technology (NET), apart from helping to address hard-to-abate emissions, it can be used to offset any type of existing emissions, and therefore distract from addressing the underlying need to decarbonise.

This points to the need for policy and technology to address decarbonisation in the economy as its primary focus, at least for the time being. This is best done via demand side management such as emissions targets for vehicles, incentives for green technologies in early stages and in certain cases, outright bans or performance standards. This influences demand for carbon-intensive sources of energy. Stronger demand side management leaves more flexibility for NETs such as DACS to focus on hard-to-abate sectors. Yet, the importance of NBS and afforestation cannot be underestimated as the first step to scale in NETs deployment.

Applying existing policy tools

Governments need to provide clear (finance relevant) policy direction, up to and including legislation and target setting, to provide business certainty. Policy tools are fairly straight forward and can be adopted from the current climate playbook:

1) Direct funding for R&D such as the EU Innovation fund[40]
2) For constructing large-scale FOAK plants in DAC Hubs as in US IRA[41]. Taking a stake in a project could also be possible or via first loss loans.
3) Direct incentives through tax credits or for production such as under the updated US provision 45Q in the US IRA's support of 180 $/tCO_2$ captured and stored and $130/t used. Importantly this can be claimed by companies capturing just 1Ktpa, which encourages early start-ups[42].
4) Carbon pricing. There is currently no carbon pricing regime that includes DACS, but regions such as the EU and China have carbon markets. These could be adapted to include DACS. In a global context, the UN's Article 6 covering carbon markets can be an important instrument.
5) Contracts for difference such as in the UK are also vehicles of support.
6) Public procurement of DACS credits and through reverse auctions could be used for price discovery and to launch major programs.
7) Development banks could become involved where applicable.

This mix of measures can be summarised into three broad approaches for governments to achieve scale:

- Bring DACS costs down via direct subsidies such as tax credits.
- Directly procure the DACS credits.
- Make the cost of DACS attractive verses emitting, through carbon markets.

Driving costs down

There is also a role for agreed Life Cycle Analysis of the various types of DACS, and accounting frameworks to assure carbon offsets that are sold either bilaterally or through the VCM. In the future, standards aligning with Article 6 will be required. At present, the demand for DACS comes from the VCM and the need for high quality credits. However, recent quality uncertainty around forestry projects is having a major impact on the VCM. The need for assurance of measurable performance of CO_2 capture looks likely to be a significant driver.

JPMorgan Chase paid 800 $/tCO_2$ in May 2023 in the VCM market after tax incentives are considered, but demand is likely to be constrained at these prices. Reaching 1GT captured by 2050 would be unlikely at these prices. While costs are expected to ultimately drop to $100-150/t, as shown in the IPR cost model in section 10, this requires a supported scale-up in the earlier stages. Accordingly, it seems incentives will have to rise substantially to start the level of scale-up that could lead to a virtuous circle towards cost reductions.

The $180/t of IRA tax benefit for DACS in the US is meaningful, but not sufficient to stimulate the multiple megaton projects that will be required to push R&D, provide learning by doing opportunities and deliver economies of scale. Furthermore, this needs to happen worldwide, not just in the US. Precise learning curves to achieve cost reductions are not easy to estimate for new technologies. On an optimistic note, governments may perceive decarbonisation of hard-to-abate sectors as reason enough to make significant investment in the next decade.

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[40] https://climte.ec.europa.eu/eu-action/eu-funding-climate-action/innovation-fund_en
[41] https://www.energy.gov/oced/DACHubs
[42] https://daccoalition.org/what-the-inflation-reduction-act-means-for-direct-air-capture/

Tackling overshoot

It is in the context of addressing overshoot of any 1.5°C temperature outcome that policy design could expand to be far more comprehensive, because if that scenario prevails, then carbon removals including DACS will be required. NBS will be hard to push much beyond the 4Gt by 2050 given the land constraints.

Overshoot with multiple significant climate events would usher in a new world, which would need to be addressed at a global level. Admittedly, deciding when overshoot of the key 1.5°C level is happening will be contentious but, by the early 2030s the IPR FPS sees this as confirmed, and average annual temperature itself will be overshooting 1.5°C in particular years, ahead of that.

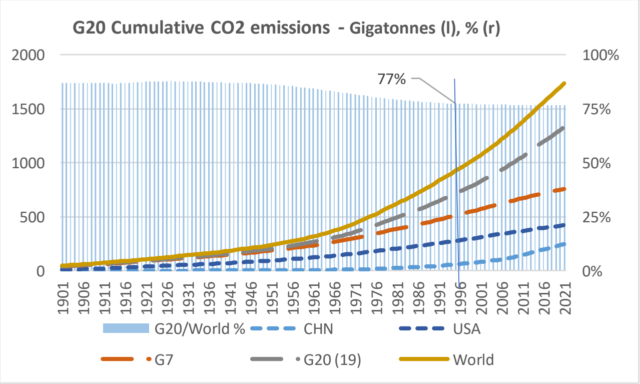
Any associated severe climate events or mass migration will bring into question who is 'responsible' for the overshoot and that will reach back into the history of emissions since the late eighteenth century. These will not be easy discussions. It is most likely discussions to resolve overshoot will start in the context of the IPCC as the apex climate body (which could begin to address the issue in the context of carbon markets under Article 6).

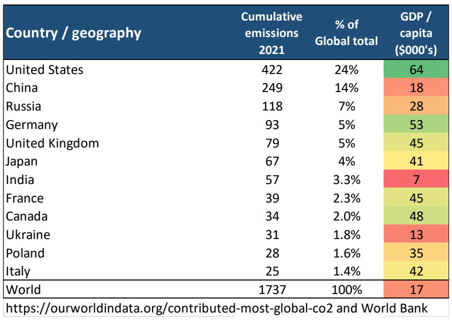
It seems likely that as overshoot happens and climate impacts gather pace, social tipping points would also be reached, leading to collective recognition that action will be required to stabilise the climate. In other words, the need to address overshoot may simply become 'inevitable.' As in the case of the Green Climate Fund, who pays for the action to address the temperature CO_2 overshoot will hold the key.

Potential role for G20

With respect to coordinating and setting the direction for collective global initiatives, the G20, which is responsible for 75% of historic emissions, has proven to be an effective apex international organisation. It brings together the wealthier nations, bridges the global North and South, and includes both hydrocarbon producing and net-hydrocarbon consuming nations. Furthermore, it has successfully addressed global issues in the past.[43] However, it is important to note that still-developing countries in the G20 make the case that the OECD members have reached a higher level of wealth, that they too have a right to achieve. Hence GDP per capita is also going to have to be considered. An agreement sponsored and paid for by the G20 may pave the way for historic emissions to be removed, and, at the same time (in effect), create a greater share in the remaining carbon budget for the smaller emerging and developing countries.

Figure 11: Left; G20 Emissions and right; cumulative emissions for the top twelve national CO_2 emitters.





Country / geography	Cumulative emissions 2021	% of Global total	GDP / capita ($000's)
United States	422	24%	64
China	249	14%	18
Russia	118	7%	28
Germany	93	5%	53
United Kingdom	79	5%	45
Japan	67	4%	41
India	57	3.3%	7
France	39	2.3%	45
Canada	34	2.0%	48
Ukraine	31	1.8%	13
Poland	28	1.6%	35
Italy	25	1.4%	42
World	1737	100%	17

https://ourworldindata.org/contributed-most-global-co2 and World Bank

Source: Authors' own illustrations.

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[43] (1) In 2008, G20 countries addressed tax planning; base erosion and profit shifting (BEPS) refers to tax planning strategies that exploit gaps. In 2023 the members of the OECD/G20 Inclusive Framework on BEPS recognised significant progress with reform of the international tax system. (2) in 2015 G20 Finance Ministers asked the Financial Stability Board (FSB) to review how the financial sector could take account of climate related issues, the outcome was the Task force for Climate-related Financial Disclosures (TCFD).

How these countries finance these costs is likely to be a heated debate. Here are some options:

- Unrestricted government borrowing, such as in Covid, would only eventuate in a true crisis that will then take some time to solve, given lags. That is always possible from the 2040s, possibly even earlier.
- Using carbon market revenues is a pathway.
- Carbon taxes skewed towards high emitters would be seen by many as an equitable approach. Indeed, it is possible that some high emitters such as oil and gas corporates have the skills and technology to deploy DAC themselves so they would be, in effect, taxed on one side of the business and rewarded on another – potentially a very effective way of netting emissions.
- Again, with the caveat that underlying trend in oil and gas use needs to be downwards. A meaningful global carbon tax would keep prices higher as demand falls, again encouraging substitution.

The case for preparing Plan B

It makes sense that policy further encourages the development of DACS within the overall context of pushing as hard as possible for low overshoot of 1.5°C, while in effect preparing a 'plan B' to tackle overshoot if and when that may be required. The IPR FPS forecasts that will be needed. There is a role for governments in the coordination and planning of DAC and storage hubs, and DAC accounting, definitions and standards to assess life cycle impacts of DAC removals all need to be developed and agreed sooner rather than later. Governments should also be bold in shouldering the costs now, to get the learning curve of reducing costs in motion, as they were once with renewable energy, particularly solar power. Planning for the longer term should not wait long.

12. Conclusions

This report has described the engineering challenge of scaling DACS within a meaningful climate frame. It has described in simple terms the three key activities: power, capture and storage, while identifying physical and geographic requirements for each and tested the scalability of those requirements. It has broken out the areas of activity and differentiated between the capture process (DAC) and the additional storage process (DACS), and it emphasised the central role for net-zero power. This study also emphasises that DACS needs to be additional to decarbonisation plans including CCS deployment for hard-to-abate point sources. CO_2 captured in the DAC process may also, in time, be used at scale for chemicals, building materials and synfuels.

Headline conclusions as follows:

- Scaling DACS for meaningful impact will be difficult, but possible;
- Technology and materials to reach 1Gt of capture capacity by 2050 exist;
- 1Gt in 2050 would be similar in scale to the existing refining industry, in addition to 2-4% of future power generation, and storage activity equivalent to one third of the current gas extraction industry;
- While CCS deployment has been driven by the proximity of carbon emission sources to storage sites, with DACS it would be driven by proximity to cheap carbon-free energy, carbon storage sites and – depending on the technology deployed – proximity to water sources as well;
- To make a climate-relevant impact, scaling to 5Gt by 2070 would be necessary;
- Exploration for geological storage may emerge as a business activity in the future;
- Current trends and trajectories indicate that the cost of DACS is too high to attract investment at scale at present. So, policy intervention is required and that may take a number of different forms;
- Policy, financing support and prioritisation may become the main challenge; and
- All these challenges have potential solutions, which could and should be examined.

These conclusions support the case that DACS should be taken seriously as an addition to the global toolbox for climate action, just as many overshoot 1.5°C scenarios imply.

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Glossary

BECCS	bioenergy with carbon capture and storage
CAPEX	capital expenditure
CCS	carbon capture and storage
CCUS	carbon capture, utilisation and storage
CDR	carbon dioxide removal
CFC	chlorofluorocarbon
CfD	contract for difference
CO_2	carbon dioxide
COP	Conference of the Parties
CSP	concentrated solar power
DAC	direct air capture
DACS	direct air capture and storage
DACCS	direct air carbon capture and sequestration
EO	ethylene oxide
EOS	economies of scale
ESA	electro-swing adsorption
ETS	emissions trading system
FEED	front-end engineering and design
FOAK	first of a kind
GEORG	Icelandic Geothermal Research Cluster
GHG	greenhouse gas
HVO	hydrotreated vegetable oil
H_2	hydrogen
H_2O	water
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
LCA	life cycle assessment
LCC	levelized cost of capture
L-DAC	liquid DAC
m-DAC	membrane-based DAC
NDT	non-destructive testing
NOAK	nth of a kind
Net Zero Scenario	Net Zero Emissions by 2050 Scenario
OPEX	operating expenses

PV	photovoltaic
PVC	polyvinyl chloride
R&D	research and development
S-DAC	solid DAC
SMR	steam methane reforming

Units of measurement

GJ	gigajoule
Gt	gigatonne
$GtCO_2$	gigatonnes of carbon dioxide
kg	kilogramme
km_2	square kilometre
Kt	thousand (kilo) tonnes
Ktpa	thousand (kilo) tonnes per year
Mt	million tonnes
Mtpa	million tonnes per year
$MtCO_2$	million tonnes of carbon dioxide
MWh	megawatt hour
THh	terawatt hour
t	tonne
tCO_2	tonne of carbon dioxide
tH_2O	tonne of water

ANNEX A: CAPTURE TECHNICAL SUMMARY

A.0 Summary table

Table 7 (reproduced from main section) summarises the key dimensions to deliver 1Mtpa of capture capacity. In the table where point estimates are given there is a range of uncertainty around each.

Table 7: DAC requirements to capture 1Mt per year.

Requirements for 1Mt of CO2 capture capacity / year	**Liquid Direct Air Capture (L-DAC)**	**Solid Direct Air Capture (S-DAC)**
Construct		
Land area	100 acres, 40 hectares, or 0.4 km2	220 acres, 90 hectares or 0.9 km2
Geography	Not super dry/cold, water, lower altitude preferred	Lower altitude preferred
Materials	50KT steel, 20KT cement	40KT steel, 10KT aluminium, 20KT cement
Chemical reactants	10KT KaOH and 20KT CaCO3	12KT Amine sorbent, Up to 20,000M3 Ceramic lattice
Technical units	Various incl. high temperature Calciner-Slaker	Up to 2,000 capture containers; Adsorbent units
Staffing	Estimated 1500 FTE's	Estimated 2000 FTE's
Permitting	Up to 5-7 years	Up to 5-7 years
Build time (excl permits)	2 years	2 years
Operate		
Water	5 MT/Year, though more in low humidity	0.1 MT/Year, with a range around that
Heat cycle	900 degrees Celsius, at atmospheric pressure	80-120 degrees Celsius; in a vacuum
Power cycle	Some flexibility, high temp calciner remains on	Demand response flexibility is possible
Material supplies	Maintentance materials likely not critical	Maintentance materials likely not critical
Chemical reactants	1KT KaOH and 1KT CACO3 per year	At least 3KT amine adsorbent (potential challenge)
Maintenance	Like large industrial site with high temp process	Similar to a large industrial site
Staffing	Estimated 100 FTE's	Estimated 100 FTE's
Risk management	Similar to a simple chemical plant	Similar to large, simple industrial process

Note: these requirements to capture 1Mt CO2/year assume a net zero 2TWHr power source.

Sources: IEA with literature review (Nature, Rhodium, others), interviews based on public information with technology experts. Where numbers are point estimates, there is a range of uncertainty around each.

A.1 Liquid Process Direct Air Capture site with capacity of 1Mt per year

The Occidental ('Oxy') – 1PointFive - Carbon Engineering 'Stratos' project[44] Ector County, (see graphic, from Carbon Engineering website) with a capacity of 0.5Mt took FID in 2022, construction started 2023[45] and it is expected to start operating mid-2025 in the Texas Permian Basin.

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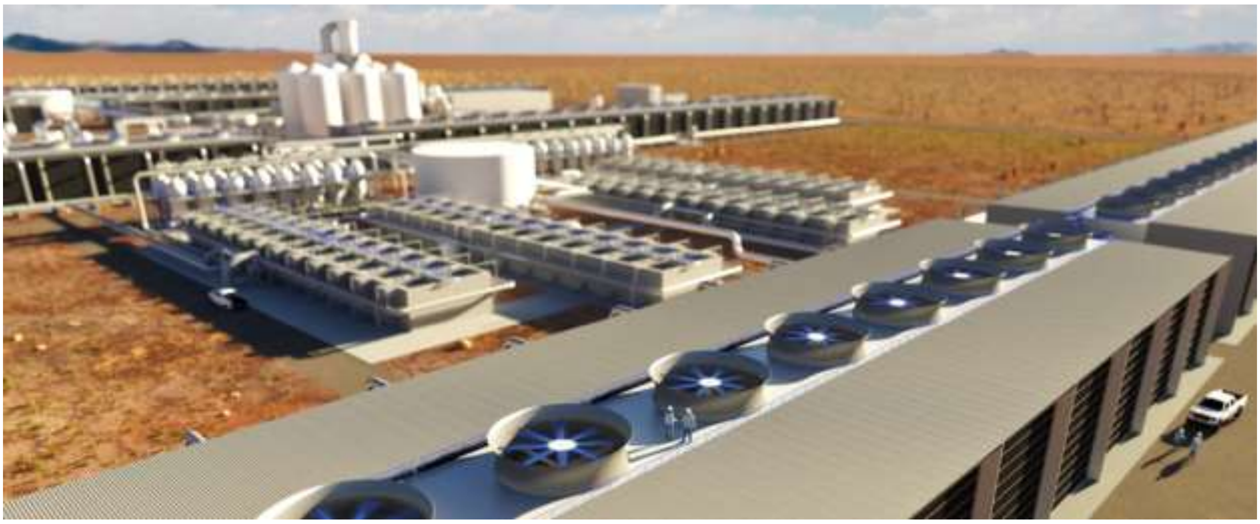
[44] Occidental and its subsidiary 1PointFive with Carbon Engineering, announcement of August 2022 link

[45] 1PointFive announcement of April 2023 link

Figure 12: Carbon Engineering – 1PointFive illustrative rendering of what a 1Mt facility may look like



Source: Carbon Engineering

With this Stratos project as a reasonable comparison, and drawing on other public information much of it from the IEA, this study concludes that a reasonable baseline on which to test scalability, starting at the 1Mt/year level, could be as follows. These numbers are the same as in the table above.

<u>Construction</u> (build requirement for 1Mt/year of capture capacity)

Land area – the site under construction is an estimated 50 acres, making the mid-range estimate for a 1Mt site is 100 acres, or 40 hectares, or 0.4 km^2 which aligns with information published by the IEA.

Geographical and atmospheric – the characteristics which favour the L-DAC process tend to be warm humid air, not super-cold nor super-dry air. And a higher air density, so a sea level location is preferred. In addition to this, access to fresh or suitably treated water is a factor.

Construction materials – Based on estimates derived from analysis published by Rhodium Group[46] the main construction requirements per 1Mt plant are 50 kt of steel, 20 kt of cement, some PVC/plastic, some aluminium for cabling, similar in volume as for a similar sized chemical plant.

Chemical reactants – seems likely initial fill would be approximately 10 Kt of KOH based on public sources and informal expert views. Assumes 10% degradation a year and annual top up of 1Ktpa. We estimate 20 kt of $CaCO_3$ with the same assumptions and a factor of two for operating flexibility.

Technical units – Air Contactor, Pellet Reactor, high temperature Calciner-Slaker, Air Separation Unit.

Staffing for **build phase** – 1500 FTE's[47] based partly on Rhodium Group study and expert opinions.

Build time (excluding design and permitting) – 2 years, estimate based on Project Stratos timeline.

<u>Operation</u> (ongoing annual requirement, per year of operation)

Water – 5 Mt/year[48]; though apparently some estimates could be up to ten times higher based on an IEA range which seems likely to correspond to (unsuitable) very dry conditions.

Heat and regeneration – 900 degrees Celsius for CO_2 capture process cycle at atmospheric pressure.

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[46] Rhodium Group, Capturing New Business, June 2020

[47] Rhodium Group, Capturing New Jobs, June 2020

[48] Page 21 IEA Direct Air Capture A Key Technology for Net Zero 2022 L-DAC water requirement 4.7 tH20/tCO2

Power cycle constraints – First liquid circuit can be switched on and off quite easily, second regeneration cycle requires a stable power or heat supply to keep the Calciner at high temperature.

Material supplies – not judged likely to be critical, similar to material requirements for maintenance for a similar chemical site to address wear and tear.

Chemical reactants[49] - 1 kt Potassium Hydroxide (KOH) + 1 kt Calcium Carbonate ($CaCO_3$) per year.

Maintenance – at level of maintenance requirements for a similar industrial site to address wear and tear.

Staffing – 100 FTE's[50] to one significant figure based on Rhodium Group study and technology experts.

Risk management – similar to a simple chemical plant, the high heat cycle temp as a potential hazard.

A.2 Solid Process Direct Air Capture site with capacity of 1Mt per year

The Climeworks[51] Orca plant, built and operating in Iceland, and the Climeworks Mammoth project, which is under construction, are both commercial small scale modular installations which could in theory be scaled (by adding lots more modules) to create a 1Mt per year super site.

Figure 13: Illustrative rendering of 36kt S-DAC plant by Climeworks, named Mammoth, currently under construction and to start operation in early 2024.

Source: Climeworks

At current levels of published capture performance[52], this would require 2000 capture containers compared to 8 at the Orca site and 72 at Mammoth. However, with large scale roll out, capture container performance will likely improve and so the total requirement for 2000 containers will likely come down.

With Orca and Mammoth (see graphic, credit Climeworks) as the most reasonable comparisons, and drawing on other public information, some of it from the IEA, this study concludes that a reasonable baseline on which to test scalability, starting at the 1Mtpa level, could be described as follows. These numbers are the same as in the table above.

<u>Construction</u> (build requirement for 1Mt per year of capture capacity)

Land area – the Orca site has 8 capture containers stacked two high, around a central control hall. Overall total footprint is 60m by 60m. If 2000 containers are stacked two high for the notional 1Mt per year super

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[49] According to technical papers and author /expert estimates.

[50] Rhodium Group, Capturing New Jobs, June 2020

[51] Climeworks partners with Carbfix for storage and is supplied by the ON's Hellisheiði Geothermal Power

[52] Current capacity is 500TCO2/year per capture container

site, equivalent footprint (scaled linearly) would be 900,000m^2, or 90 hectares, or 220 acres. This is slightly lower than estimates in the range of 1.2 to 1.7 km2 published by the IEA.

Geographical and atmospheric – the atmospheric characteristic which favours the S-DAC process tends to be a higher air density[53], so a sea level location is preferred. With respect to humidity. technology providers indicate that sorbents can be developed for both humid and dry conditions.

Construction materials – Based on interviews and some estimates derived from Rhodium Group[54] the construction requirements per 1Mt plant could be 40 kt of steel, 10 kt Aluminium, 20 kt of cement, and some PVC/plastic.

Chemical reactants – seems likely initial fill would be approximately 12 Kt of amine based on author estimate, public sources and informal expert views. Assumes 25% degradation a year and annual top up of 3 ktpa. Associated with the solid sorbent is the lattice to which the sorbent is fixed. Informal (author) estimate would be that that 10 cubic metres of lattice constructed from ceramic monolith might be required for a capture container with 6 capture units onboard, in other words each unit has an active air filter volume of between 1M3 and 2M3.

Technical units – Up to 2000[55] capture containers each with 6 capture units with adsorbent filter screens, (expensive), vacuum chambers and pump, blower, and contactor.

Staffing for build phase – 2000 FTE's[56] based on the Rhodium Group study and informal SME views.

Build time (excluding permitting) – 2 years depending on availability of container and sorbent manufacturing capacity, a view tested in interview with technology experts.

Operation (ongoing requirement, per year of operation)

Water – 0.1Mt[57] per year for a capture capacity of 1Mt per year; note that to pump CO_2 downhole in some conditions water is required (see Storage section).

Heat and regeneration – 80-120 degrees Celsius for CO_2 capture process cycle in a vacuum chamber.

Power cycle constraints – while capture container units cannot be switched on and off instantaneously, the expert view seems to be that some powering down and up again is possible in response to a power source that is cyclical, like solar (daily) or wind (dependent on atmospherics). Current design expectations indicate that S-DAC might get from 100% to 30% capacity in 1 minute, it would take about 30 minutes to fully shut down a plant as a few pieces of equipment need to be purged and emptied.

Material supplies – not judged likely to be critical, similar to material requirements for maintenance for a similar industrial site to address wear and tear.

Chemical reactants – In the future this "may be reduced to" 3 kt per year of amine-based[58] adsorbent, the author found no way of confirming it is not a lot higher than this, nor what is the upper limit (i.e. current operating requirement in today's capture containers). The operational requirement may also include silica (or other) lattice repair. While the current total volume of sorbent required does not have a publicly available upper limit, there does seem to be agreement that the chemical elements themselves are available. It is the manufacturing capacity which would be the current bottleneck.

Maintenance - similar to maintenance requirements for a similar industrial site to address wear and tear.

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[53] Technical expert view

[54] Rhodium Group, Capturing New Business, June 2020

[55] Technology expert estimates "1Mt air capture capacity would require 100's not 1000's of container units"; and Climeworks current capture container capacity is 500t/year.

[56] Rhodium Group, Capturing New Jobs, June 2020

[57] Indicative requirement is 0.1 tonne per tonne of CO2 according to CarbonCapture Bison Development Wyoming Sweetwater Townhall Q&A notes

[58] "Results show for the adsorbent (amine on silica), the future plant is expected to reduce adsorbent consumption to 3 g adsorbent per kilogram CO2. The required amine and silica would correspond to 17.4% of the global production of ethanolamine and synthetic amorphous silica. Ethanolamine is a precursor of polyethyleneimine that is used as amine for the adsorbent amine on silica." Nature, Life-cycle assessment of an industrial direct air capture process based on temperature–vacuum swing adsorption, 2021.

Staffing – 100 FTE's[59] to one significant figure based on Rhodium Group study and technology experts.

Risk management – similar to a simple industrial plant, the vacuum chamber low heat cycle would require monitoring and attention.

Figure 15: Artist's rendering of Project Bison, Wyoming, which remains in the design phase

Source: Carbon Capture Inc public materials.

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[59] Rhodium Group, Capturing New Jobs, June 2020

ANNEX B: POWER TECHNICAL SUMMARY

B.0 Summary Table

Table 8: Dimensions of Net Zero power generation to deliver 2TWh per year

Requirements for 2TWHrs (TeraWatt-Hours) per year	Solar	Wind	Hydro	Geothermal	Waste Heat	Gas plus CCS	Nuclear
Construct							
Nameplate capacity	1,420 MW	430 MW	500 MW	254 MW	380 MW	285 MW	248 MW
Capacity factor	18%	53%	45%	90%	60%	80%	92%
Inherent cyclicity	Daily, seasonal, weather	Atmospherics, seasonal	Seasonal, climatic	Stable, wellbore dependent	Industrial plant dependent	Stable	Very stable
Natural resource	>3 peak hours	>6m/s average	river with elevation, rainfall	tectonic boundaries	Heavy industry, load factor >= 60%	Natural gas	Uranium
Land area	8 KM2	64 KM2	15KM2	1KM2 (basaltic) 15KM2 (continental)	0.1KM2	2 KM2 (including gas gathering)	0.5KM2
Materials	Steel 77Kt, Concrete 69Kt, Glass 53Kt, Plastic 10Kt	Concrete 153 Kt, Steel 49 Kt, Polymers 49 Kt, Glass/carbon composites 8 Kt	Concrete 2.6 Mt, Steel 210 Kt	Steel, working fluid	build material, generator	Steel, concrete, chromium for gas gathering and power plant.	Steel 2kt, concrete 6 kt, 45 t enriched Uranium oxide
Rare Elements	Silver (Ag), Cadmium (Cd), Tellurium (Te), Indium (In), Gallium (Ga), Selenium (Se), Germanium (Ge)	Neodymium (Nd), Dysprosium (Dy)	for standard turbines	n/a	n/a	n/a	n/a
Cables	14KM	70KM	n/a	50KM	n/a	n/a	n/a
Technical units	Inverters, Transformers	Blades, pylons, generators, gears	Dam, intake, generator	Pumps, heat exchangers	Pumps, heat exchangers	well tubing, flowlines, gas processing, compressors, transmission lines, heat exchangers, turbines, generator	Small Modular Reactor (SMR)
Permitting	1-5 years	1-5 years	2-10 years	1-5 years	1-5 years	1-5 years	2-20 years
Build time	18 months	2 years	6 - 10 years	Up to 10 years	2 years	4 years	4 years
Operate							
Material supplies	low level	Spares, lubricants	low level	new well materials,	low level	Gas, spares	Uranium
Maintenance	low, then panel replacement	regular, then replace pylons	testing, bearing replacement	testing, lubes, new wells	testing, lubes, heat exchange	testing, repairs and monitoring	testing and monitoring
Staffing	4 FTE's	50 FTE's	50 FTE's	50 FTE's	100 FTE's	50 FTE's	50 FTE's
Risk management	Very low risk	Wildlife, blade damage	Dam collapse, variable rainfall patterns	Thermal output, seismicity	Reliant on industrial activity	Loss of containment, public opinion, continued supply	Obtaining consent, Loss of containment

Source: Penspen Analysis.

Note: Where point estimates are given, there is a range of uncertainty around that point. This annex B has details behind the information in this table.

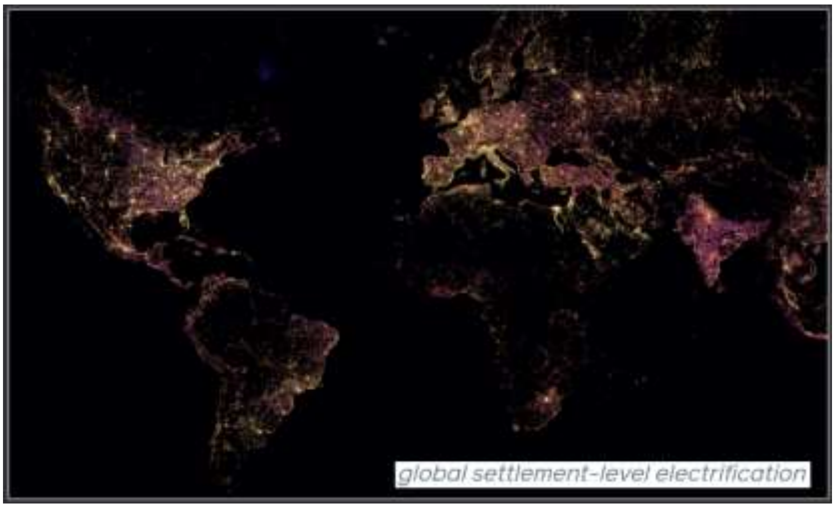
Decarbonized national power grids: in an ideal world, net zero national power grids would be available to deliver electric power to many, if not all, large-scale DAC plants. However, existing national grids may not be able to deliver sufficient power for large scale DAC and storage any time soon. That is because there is demand for that electricity today, and the demand is set to increase in future as populations expand, standards of living improve, and carbon intense activities like home and business heating, mobility and heavy industry are increasingly electrified.

Furthermore, in addition to the increase in demand for electrons, there are already significant bottlenecks in existing networks attempting to decarbonize, to transmit more power longer distances, connect existing grid infrastructure to newly built renewable power generation, and enabling a step change in power delivery infrastructure where demand is increasing to such an extent that existing cabling and distribution equipment cannot, for example, deliver high currents to fast charge electric vehicles. So power grids may eventually catch up but if massive roll out and scale up of DAC and storage is going to start now, DAC plants are more likely to succeed if they plan for their own renewable power.

Many favourable DAC locations where net zero power and capture conditions and storage potential coincide are not close to existing grid infrastructure (see diagram).

On the other hand, DACS plants working part-supplied by net zero national grids may help with peak shaving and otherwise managing supply-demand imbalance.

Figure 17: Global settlement level electrification[60]



Smoothing, this study has *not* analysed the options and methods for smoothing of intermittent renewable power especially in the case of solar or wind. If the power-capture-storage infrastructure is off grid, and that may indeed by the case (see sub-section on grid availability below), then some kind of smoothing mechanism would be required. Exactly what kind of smoothing technology is deployed would depend on the type of capture plant, local conditions and system optimisation factors.

B.1 Solar

Solar power has very wide geographical applicability, is very easy to implement with many suitable contractors and manufacturers, requires minimal maintenance, requires minimal staffing, creates no noise, are easy to remove/dismantle, and the materials are recyclable. Solar panels are also becoming increasingly efficient.

The disadvantages are that the manufacture of solar panels uses several rare elements, which will be under increasing pressure with the vast number of solar farms planned (although requirements are reducing as manufacturing methods improve), they use a relatively large amount of space, which can't be used for anything else, the life can be relatively short with degradation, and a requirement for replacement and use for DAC means highly cyclic loading with power available during the day, but not at night and limited on cloudy days (average load factor is 18%).

The connected DAC plant must be designed to accommodate this as efficiently as possible. Also, areas receiving high peak solar hours tend to be arid, which conflicts with the current L-DAC requirement for a plentiful water supply.

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[60] Engineering at Meta, A new predictive model for more accurate electrical grid mapping, 2019 link

Construction (build requirement for 2TWh of annual power production)

Nameplate capacity – 1,420 MW

Capacity factor – 18%

Inherent cyclicity - Daily, seasonal, weather.

Natural resource – Sun > 3 peak average sun hours (load factor 13%) depending on location[61]

Land area – 8 M2 midrange, but depending on location.

Materials[62] – Kilo tonnes[63] of Glass, Steel, Concrete, Aluminium, Silicon, Copper, Plastic.

Rare Elements [62] – Tellurium (Te), Germanium (Ge), Cadmium (Cd), Selenium (Se), Indium (In), Gallium (Ga), Silver (Ag)[64].

Cables – 14km

Technical units - Inverter, step-up transformers, control system.

Build time (excluding permitting) – 18 months.

Operation (ongoing requirement per year of operation)

Material supplies – Minimal in the short term, replacement panels after 20 – 30 years.

Maintenance - Minimal maintenance. Removal of dirt and debris, removal of plant growth between panels. Monitoring and replacement of panels as they degrade. Life is 20 to 30 years.

Staffing – 4 FTEs

Risk management – Very low risk.

B.2 Wind

Wind power has very wide geographical applicability with a relatively high average load factor of 53%, Most coastal locations are favourable, because of the sea breeze (wind that blows from large body of water towards and onto a landmass, due to differences in air pressure created by the differing heat capacities of water and dry land), as are elevated locations. It is very easy to implement with many suitable contractors and manufacturers.

Wind turbines available are extremely efficient. Although the overall scale of wind farms is large, the land in between is usable for solar farms or agriculture. The actual unusable land in a wind farm is minimal. Disadvantages are that it threatens wildlife from the impact of turbine blades, and the noise generated disturbs their habitat.

However, more recent designs have reduced the noise emissions. Another disadvantage is that the manufacture of wind turbines uses several rare elements, which will be under increasing pressure with the vast number of wind farms planned (although requirements are reducing as manufacturing methods improve, which could influence technology selection).

Maintenance is required with Non-Destructive Testing (NDT) and replacement of lubricants, filters, and parts as they wear. Use for DAC means highly cyclic loading with power available only when the wind blows. There are several different technologies, including Direct Drive - Electrically Excited Synchronous Generator (DD-EESG), Direct Drive - Permanent Magnet Synchronous Generator (DD-PMSG), Gear Box - Permanent Magnet Synchronous Generator (GB-PMSG) and Gear Box - Double-Fed Induction Generator (GB-DFIG), with GB-DFIG currently being the most dominant.

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[61] Global Solar Atlas

[62] Raw materials demand for wind and solar PV technologies in the transition towards a decarbonised energy system. Carrara, S., Alves Dias, P., Plazzotta, B., Pavel, C. EUR 30095 EN

[63] Steel 74Kt, Concrete 67Kt, Glass 51Kt, Plastic 9Kt, Aluminium 8Kt, Silicon 5Kt, Copper 5Kt

[64] Tellurium (Te) 29t, Germanium (Ge) 27t, Tellurium 25t, Indium 21t, Indium (In) 11t, Gallium (Ga) 7t, Silver (Ag) 5t

Construction (build requirement for 2TWh of annual power production)

Nameplate capacity – 430 MW

Capacity factor – 53%

Inherent cyclicity – Depends on prevailing atmospherics and weather patterns, which are less predictable than the 24-hour day/night cycle for the sun. There is also the overlay of a seasonal variation.

Natural resource – Wind[65] > 6m/s annual average wind speeds .

Land area – 64 M2 midrange. The overall requirement is based on the required spacing between turbines to obtain optimum efficiency (6 rotor diameters); however, the land between turbines is usable for agriculture or a solar farm.

Materials – Kilo tonnes[66] of Concrete, Steel, Polymers, Glass/carbon composites, Aluminium, Copper, Iron Zinc.

Rare Elements – Tonnes[67] of Boron, Chromium, Dysprosium, Manganese, Molybdenum, Neodymium, Nickel Praseodymium, Terbium.

Cables – 70km

Technical units - Blades, gearbox, generator, controller, rectifiers, and inverters (depending on the system), step-up transformers, control system.

Build time (excluding permitting) – 2 years.

Operation (ongoing requirement, per year of operation)

Material supplies – Lubricants and spare parts.

Maintenance - Regular inspection, changing of lubricants and filters, replacement parts. Design life is 25 years.

Staffing – 50 FTEs

Risk management – Threat to the wildlife. Damage to the blades caused by bird strikes, lightning strikes, rainfall, blade furniture detachment, delamination, leading-edge corrosion, or blade cracks.

B.3 Hydro

Hydroelectric power is only suitable for mountainous regions receiving a high level of rainfall, or a large river. Load factor can be very varied for 0.45 to 0.8.[68] The largest power plant in the world is the Three Gorges dam with an installed capacity of 22,000 MW and an annual energy generation of 95 +/- 20TWh.

The alteration to land use is significant with the flooding of river valleys or gorges with significant impact on local populations in the flooded area, as for land-based wildlife, and waterborne wildlife such as migrating fish, although fish ladders can be used. Some reservoirs create recreational areas.

The amount of material used can be vast, with Mt of concrete and Kt of steel and with planning and construction taking 6 to 10 years. Although applicable in some areas, it is not scalable enough for the number of global DAC sites required.

Construction (build requirement for 2TWhr of annual power production)

Nameplate capacity – 500MW

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[65] Load factors vary between 0.35 to 0.7, with offshore wind consistently high for most coastal areas. 22% likely to be offshore; source is FUTURE OF WIND Deployment, investment, technology, grid integration and socio-economic aspects - IRENA 2019

[66] Concrete 153 Kt, Steel 49 Kt, Polymers 49 Kt, Iron (cast) (Fe) 8 Kt, Glass/carbon composites 3 Kt, Zinc (Zn) 2 Kt, Aluminium (Al), 1 Kt, Copper (Cu) 1 Kt

[67] Chromium (Cr), Nickel (Ni), Molybdenum (Mo), Neodymium (Nd), Dysprosium (Dy), Boron (B), Praseodymium (Pr) and Terbium (Tb)

[68] IRENA 2020

Capacity factor – 45%

Inherent cyclicity - Seasonal and dependent on climatic conditions that deliver rainfall upstream.

Natural resource - Elevation and rainfall with the scale of large continental rivers and hundreds of metres of hydraulic head.[69]

Land area – The area behind a dam is typically 14 km^2[70]. The power plant itself is only 0.5km^2.

Materials – 2,600,000 tonnes of concrete and 200,000 tonnes of steel.[71]

Cables – Depends on the location of DAC relative to the power plant.

Technical units - Dam, intake, penstock, sluice, Turbine, generator, step-up transformers, control system.

Build time (excluding permitting) – 6-10 years.

<u>Operation</u> (ongoing requirement, per year of operation)

Material supplies – Limited to low level maintenance consumables and spares.

Maintenance – Non-destructive testing (NDT) of equipment, bearing replacement, changing drive couplings and belts, including realignment, Sensor replacement and calibration, major mechanical and electrical or civil engineering repairs and refurbishments.

Staffing – 50 FTEs

Risk management –Dam collapse; environmental change, and reduced rainfall is challenging to manage.

B.4 Geothermal

Geothermal power is limited to tectonic plate boundaries where high-temperature geothermal resources are close to the surface. The number of wells required for 2TWh can be between 70 and 150, with new wells being periodically required. Land use is high with wells and power plants spread over a large area.

Although geothermal power plants are spread over large areas their impact is typically minimal. The load factor is excellent and typically high at 90% with power being produced continuously.

The disadvantage is that geothermal relies on careful reservoir management, and it is very location specific. Plants are prone to seismic risks and can cause earthquakes in extreme cases. Geothermal energy can use water/steam as the primary fluid for energy generation or an Organic Rankin Cycle (ORC).

Although applicable in some areas, the narrow range of locations and build time means it may well not be scalable for the global DAC sites required.

<u>Construction</u> (build requirement for 2TWhr of annual power production)

Nameplate capacity – 254 MW

Capacity factor – 90%

Inherent cyclicity – Stable.

Natural resource – Geothermal heat close to the surface. This is typically at the edges of tectonic plates.

Land area – Variable depending on geology from 15km^2 (US continental) to 1km^2 (Iceland mid ocean ridge basalt); this assumes 60 wells and 3 power plants[72]; with some informal opinion on Iceland example

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[69] A river the size of the Thames would need more than 600m hydraulic head to generate 300 MW. Load factors vary between 0.25 and 0.8, source IRENA (International Renewable Agency 2020)

[70] Dorber, Martin, Roel May, and Francesca Verones. 2018. "Modelling Net Land Occupation of Hydropower Reservoirs in Norway for Use in Life Cycle Assessment." Environmental Science & Technology 52 (4):2375-2384. doi: 10.1021/acs.est.7b05125.

[71] https://www.freeingenergy.com/math/hyrdo-hydropower-dam-concrete-cement-mwh-gwh-m151/

[72] U.S. Geological Survey, Geyser power plant

Materials - Working fluids include dry steam, hydrofluorocarbons such as R134a, R245fa, isobutane, pentane, propane, and Perfluorocarbons. Also needs stainless steel for well tubing and concrete.

Cables – 50 km.

Technical units – Can be an open cycle or binary Organic Rankine Cycle (ORC) - Pumps, heat exchangers, turbine, generator, step-up transformers.

Build time (excluding permitting) – Up to 10 years, which will likely be significantly reduced.

<u>Operation</u> (ongoing requirement per year of operation)

Material supplies – Material for new wells, so pipe, cement, and tubing.

Maintenance - Non-destructive testing (NDT) of pressure-containing equipment, testing of safety systems, checking of lubrication, changing of filters, electrical system testing, vibration monitoring, maintenance of heat exchangers. If new wells are constructed, then drilling and completing with a rig.

Staffing – 50 FTEs

Risk management - Thermal site capacity (may fall short) and seismic risks.

B.5 (Industrial) Waste Heat

Many industrial processes use heat and in most cases this heat is lost to the environment. The most heat-intensive sectors are oil refining, iron and steel, food and drink, pulp and paper, chemicals, glass, cement, and ceramics. Heat output is contained within solid materials, such as sludge, gas, or liquids. Much of it is below the boiling point of water. Heat is recovered and turned into power using heat exchangers and either a single Organic Rankin Cycle (ORC) or multiple cycles as in the Kaline Cycle.

These systems are commercially available and become more common with energy transition targets and the cost of fuel. Generally, they are commercially viable if the capacity factor exceeds or is equal to 60%. To reach 2TWh, power would have to be generated from multiple sites, with metal production contributing 60 MW per site, chemicals 20 MW per site, glass manufacturing 25 MW per site and refining 5 MW per site.

These sites typically work 24hrs a day, with shutdowns only for maintenance. One industrial cluster comprising multiple industries might only produce half of that required for a 1Mt DAC site, so there will not be enough available to scale up to 1000+ sites.

<u>Construction</u> (build requirement for 2TWhr of annual power production).

Nameplate capacity – 380 MW

Capacity factor – 60%

Inherent cyclicity – Depends on the industrial plant.

Existing resource – No natural resources are required.

Land area - 0.01 km^2 per site, likely integrated with the existing site.

Materials - 28,500 tons of steel, concrete, working fluid (Hydrofluorocarbons such as R134a, R245fa, isobutane, pentane, propane, and perfluorocarbons).

Cables - This would be high depending on the location of industrial heat sources and DAC plant. It would be logical/practical to install waste heat recovery at several industrial plants close together as part of an industrial cluster.

Technical units - Assume binary cycle with Organic Rankine Cycle - Pumps, heat exchangers, turbine, generator, step up transformers.

Build time (excluding permitting) – 2 years, most of the equipment is Other Equipment Manufacturer (OEM).

<u>Operation</u> (ongoing requirement, per year of operation).

Material supplies – For maintenance and spare.

Maintenance – Non-destructive testing (NDT) of pressure containing equipment, testing of safety systems, checking of lubrication, changing of filters, electrical system testing, vibration monitoring, maintain of heat exchangers.

Staffing – 100 FTEs.

Risk management – Reliance on continued operation of the industrial plant.

B.6 Natural Gas with Carbon Capture and Storage (CCS)

For some DAC process units (notably Oxy-CE Stratos), using natural gas is economically sensible and scientifically sound in that CO2 from the gas burned does not enter the atmosphere.

In this example of gas plus CCS, we have assumed that power and therefore gas demand exceeds what any local gas grid might deliver, and therefore that the power generation plant is collocated or connected by pipe to its own gas extraction facility.

In practical terms, 75% of the gas provides heat, 25% through a gas turbine and generator satisfies the electrical requirements, with storage capacity needing to exceed the atmospheric CO_2 capture plant capacity by around 30%. The CO_2 produced from burning the natural gas is stored alongside the atmospheric carbon captured through the DAC process.

Gas-fired power generation accounts for around 25% of global electricity production. Capacity factors for gas-fired power plants in a mix of power sources, including renewables, are likely to reduce significantly as cheaper and less carbon-intensive alternatives displace the power source. However, if dedicated to DACS, it can be expected to be around 80%.

The advantage of using natural gas is that it satisfies the heat requirements of the existing DACS process, requiring no new development, it is a very mature technology, and gas can be delivered through pipelines or liquefied and shipped over long distances. One disadvantage is that some oppose who oppose all future fossil fuel use, may object to natural gas plus CCS.

Notwithstanding, it’s possible that natural gas plus CCS for DACS may become the ‘best last’ use of gas.

Construction (build requirement for 2TWhr of annual power production)

Nameplate capacity – 285 MW (75% of the power requirement is gas used directly for heat).

Capacity factor – 80% (high)

Inherent cyclicity – Very stable.

Natural resource – Natural gas.

Land area – 2 km^2 considering the gas gathering. The CC will be integrated with the DAC plant and the electrical generating plant co-located so that additional land use for generation will be minimal.

Materials Steel, concrete, and chromium for the power plant and gas-gathering infrastructure.

Cables - Negligible since power generation would be close to the DAC plant.

Technical units – well tubing, flowlines, gas processing, compressors, transmission lines, heat exchangers, turbines, generator.

Build time (excluding permitting) – 2.5 years for the power plant and 4 years for the gas gathering.

Operation (ongoing requirement per year of operation)

Material supplies – Natural gas, spares.

Maintenance – Non-destructive testing (NDT) of pressure-containing equipment, testing of safety systems, checking of lubrication, changing of filters, electrical system testing, vibration monitoring, and maintenance of heat exchangers. Design life is 30 years.

Staffing – 50 FTEs

Risk management – Societal safety risk due to gas transportation, public opinion on the continued use of gas and supply disruption (political or physical).

B.7 Nuclear

Small modular reactors (SMRs) are advanced nuclear reactors that have a power capacity of up to 300 MW(e) per unit, which is about one-third of the generating capacity of traditional nuclear power reactors. There are more than 80 commercial SMR designs.[73] Average load factors for existing operating reactors is 92%.

The significant advantages of SMRs are the power density, with a very small plot area requirements and the relative abundance of uranium (Uranium is approximately as common as tin or zinc), some plants, depending on the design, are anticipated to operate for 30 years without replenishment of uranium. Uranium requires enrichment. The percentage of U-235 varies widely, but it is consistently below 20%.

The disadvantages are that SMRs do not currently exist, so need to be developed, overcoming political hurdles to reduce the currently very long anticipated build, and permitting timeframes, and safety concerns regarding operating, production and transportation of fuel and waste. For these reasons it is not considered a rational choice for considering 1000+ DAC plants on a global scale.

Construction (build requirement for 2TWhr of annual power production)

Nameplate capacity – 248 MW

Capacity factor – 92% (high).

Inherent cyclicity – Very stable.

Natural resource - Natural uranium.

Land area - .5 km2 or less. The emergency planning zone required is designed to be no more than about 300 m radius. Potential for sub-grade (underground or underwater) location of the reactor unit providing more protection.

Materials – for Small Modular Reactor (SMR), 50 tons of steel, concrete, chromium, nickel (Stainless steel), enriched uranium (% U-235 varies widely, but it is consistently below 20).

Cables - Negligible since power generation would be close to the DAC plant.

Technical units - Small Modular Reactor (SMR) using a pressurised water reactor (PWR); with reactor pressure vessel, reactor coolant pump, steam generator, turbine, generator, pumps, condenser, step-up transformers, safety systems.

Build time (excluding permitting) – 4 years.

Operation (ongoing requirement, per year of operation)

Material supplies - Natural uranium, which requires enrichment. The refuelling cycle can be from 1.5 years to 30 years, depending on the design.

Maintenance – Non-destructive testing (NDT) of pressure-containing equipment, testing of safety systems, checking of lubrication, changing of filters, electrical system testing, vibration monitoring, maintenance of heat exchangers. Design life is 60 years.

Staffing – 50 FTEs

Risk management - Loss of containment, workers exposed to radiation. Compared to existing reactors, proposed SMR designs are generally more straightforward, and the safety concept for SMRs often relies more on passive systems and inherent safety characteristics of the reactor, such as low power and operating pressure. Multiple safety systems are implemented and supported by inspection and testing.

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[73] International Atomic Energy Agency

B.8 Brief notes on Concentrated Solar Power CSP

Concentrated Solar Power (CSP) uses mirrors or lenses to concentrate sunlight onto a small area, typically a receiver, to generate high-temperature heat. The fundamental components of a CSP system are a solar collector (parabolic troughs, solar power towers, and parabolic dishes) and receiver (filled with a heat transfer fluid, such as oil or molten salt), which can be combined with a thermal energy store.

The heat can be used for power generation using a thermodynamic power cycle or a thermoelectric generator, or to drive any process that requires heat such as desalination, gasification, chemical and metals production, and the production of hydrogen through high-temperature electrolysis.

CSP + thermodynamic power cycle and photovoltaic (PV) solar power have similar efficiencies and load factors when generating electricity, however the heat from CSP can be used directly in the DAC process and the thermal store capability can be used to reduce or eliminate intermittency. The heat generated by CSP depends on the solar collector type but can be as high as 1,500 deg C with 900 deg C required by the L-DAC process.

Considering 80% of the energy requirement within the L-DAC process is heat, the use of CSP could potentially increase the efficiency of the solar energy collection to heat aspect of the process by 300%. The combination of CSP and DAC in some geographical areas could be a viable and more sustainable alternative in comparison with other sources of heat such as natural gas, hydrogen or yet-to-be-developed electrical heat solutions.

Figure 18: Gemasolar power plant[74] of 20MW with central tower receiver, a heliostat field on 185ha of land and a molten-salt heat storage system

Source: Sener Group

B.9 Proximity to a net zero power source

Solar and wind: given the cyclical nature of solar and wind, in practice good locations would be coastal locations for wind with plentiful sunshine for solar. In practice the following seem to be well suited for a combination of solar and wind power:

- Equatorial and subtropical coastal locations with sun, including west coast of North America, South America, Northwest, Southern and Eastern ‘Horn of’ Africa, Arabia and much of Australia.
- Arid central regions with higher average wind, including in Central North America, Central Argentina, Saharan Africa, Arabian Peninsula and inland China.
- Some scenarios (Shell Sky 2050) envision DAC rollout in Mali, Niger, Sudan and Chad, partly due to the potential availability of renewable resources.

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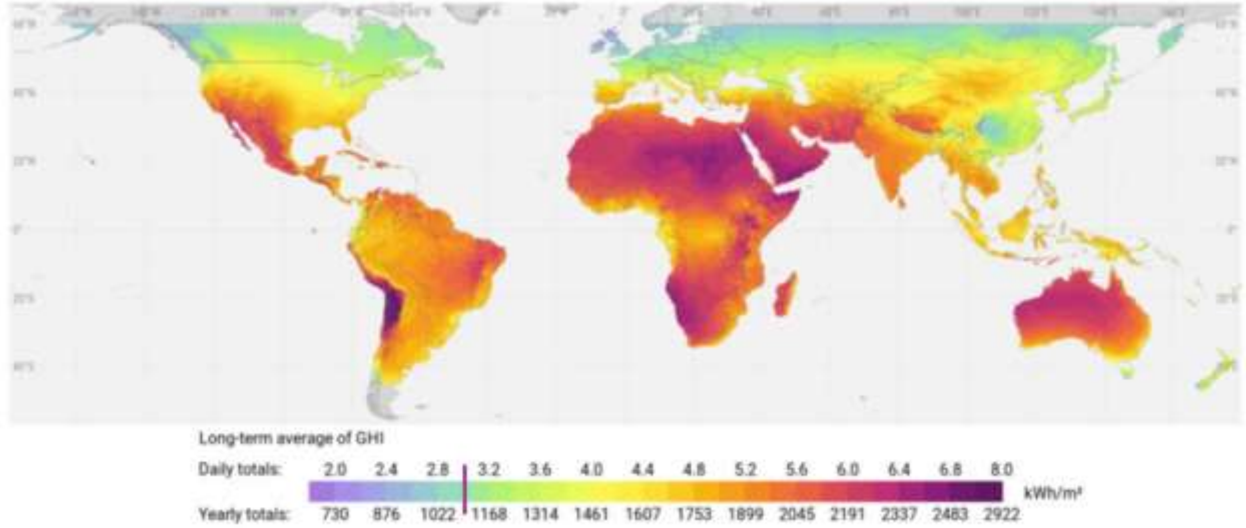
[74] Renewable Power, Gemasolar Concentrated Solar Power, Seville, article as per 2023 version with link

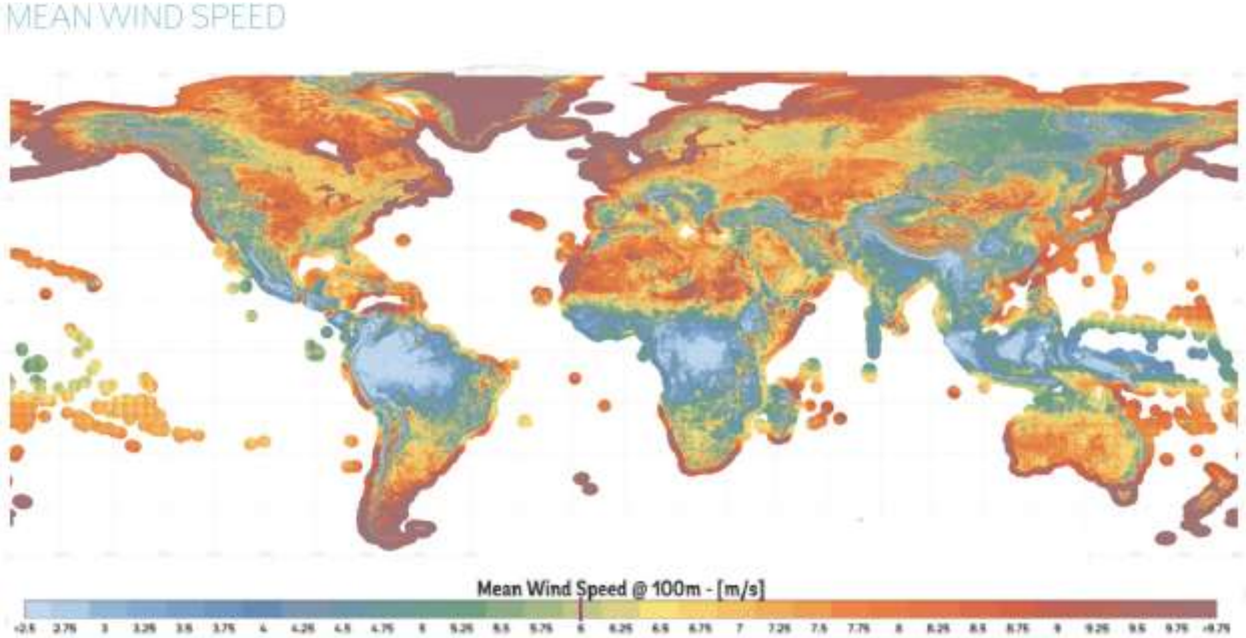
Figure 19: Solar photo voltaic power potential



Source: Global Solar Atlas, link

Note: solar potential of 3kWh/m2, which corresponds to 3 peak sun hours a day, is marked on the key scale.

Figure 20: Wind power potential, more than average of 6m/s (marked)



Source: Global Wind Atlas, link

Alternative net zero power sources: geothermal may be better suited to the S-DAC process with its lower temperature heat cycle; geothermal potential is higher at tectonic plate boundaries, particularly:

- West coast of the Americas, especially west Canada and Southern Chile,
- Where volcanic islands and countries exist, associated with mid-ocean ridge volcanic activity,
- Active tectonic belt through central Europe from Germany, through Greece to Turkey,
- Southern extent of the Red Sea between Africa and the Arabian peninsular,
- Volcanic regions of Indonesia, Philippines and from Japan to the Aleutian Islands,
- New Zealand particularly the north and south coastal regions.

Figure 21: Geothermal power potential

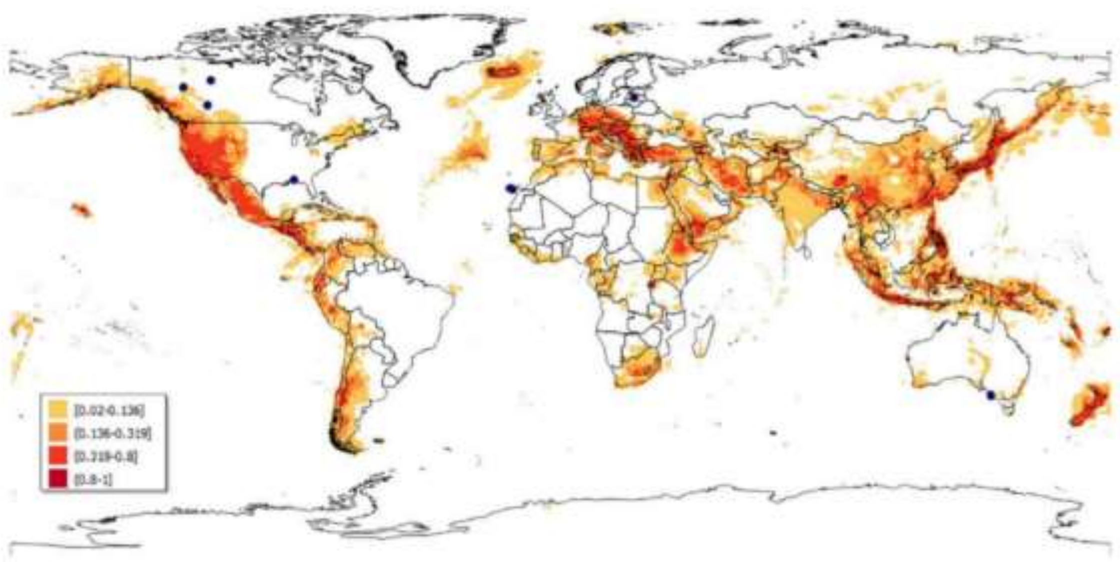
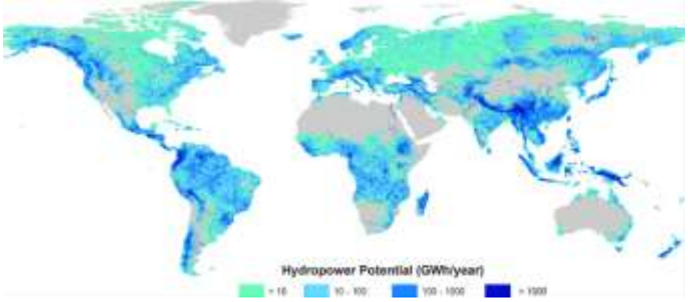


Fig. 3. Optimal geothermal suitability distribution produced by the Maximum Entropy model using all parameters. Warmer colours indicate higher suitability scores. Dots indicate geothermal power plants in the test set whose suitability is not predicted by the model.

Source: Coro Trumpy, based on the output of an entropy model.

Figure 22: Map of hydropower potential



Source: Hoes Meijer 2017

Hydro power depends on high local or upstream rainfall, and sufficiently mountainous terrain to allow the construction of a dam. This embedded map (source: Hoes Meijer 2017) indicates preferred locations. Best hydro potential seems to be in the mountainous regions of western Canada, Colombia and Chile, central America, the alpine regions in Norway and across central and southern Europe, some locations in western Africa and Ethiopea in the east, the Himalayan mountains and surrounding drainage basins. Note that build time for hydro plants is long.

Waste industrial heat depends on industrial clusters, which rarely generate the continuous 500MW-equivalent level of heat required to power DAC at scale.

Nuclear power can be fairly flexible though it does require cooling water, and a stable tectonic location, so coastal locations in higher latitudes, away from seismic activity, are preferred.

ANNEX C: STORAGE AND TRANSPORT TECHNICAL SUMMARY

C.0 Summary Table

This Annex provides the detail behind the key Storage table (copied here for easy reference).

Table 9: Dimensions to store or transport 1Mt CO_2 per year

Requirements for 1Mt Storage per year	Oil and gas	Saline aquifer	Ultramafic /basaltic	Pipe Transport CO2 100km	Ship Transport CO2 1000km
Find / develop					
Geological feature	Stratigraphic, residual, solubility	Stratigraphic, residual, solubility, mineralisation	Fracked basalt, with mineralisation	N/A	N/A
Land requirement	Minimal, downhole acreage tbc'd	Minimal, downhole acreage tbc'd	Minimal, downhole acreage tbc'd	40m for work, 10m wayleave	.05 km2 for liquefaction, storage and jetty
Materials	Carbon steel, nickel, chromium, cement downhole	Carbon steel, nickel, chromium, cement downhole	Carbon steel, nickel, chromium, cement downhole	Steel, zinc and polymers	Steel, and nickel for cryogenic tanks
Technical units	Well-head and monitoring equipment	Drilling, pipe, well-head and monitoring	Drilling, pipe, well-head and monitoring	Compressors, block valves,	Compressors, refrigeration, insulated spherical tanks, pumps.
Permitting & de-risking	4 -12 years	4 -12 years	4 -12 years	2-10 years	2-5 years
Build time (excl permits)	1-5 years	2-5 years	2-5 years	2-3 years	2-5 years
Operate					
Material supplies	Well tubing, drilling materials, power for injection	Well tubing, drilling materials, power for injection	Well tubing, drilling materials, some power for injection	Power for compression,	Power for compression and liquefaction
Maintenance	Testing and measurement	Testing and measurement	Testing and measurement	Surveillance, testing, pigging, ground care	Hull and rotating equipment maintenance
Staffing	10 FTE's	10 FTE's	10 FTE's	20 FTE's	20 FTE's
Risk management	Management, seal penetration, well integrity	Management, seal penetration, well integrity	Management, well integrity	Pipe integrity	Loss of CO2 cargo through collision
Assure storage	Legacy wells represent trap integrity risks	Monitor to assure storage	Monitor to assure storage	N/A	N/A

C.1 Depleted Oil & Gas Reservoir

Find and develop (build requirement to permanently store 1Mt of CO_2 per year)

Geological feature – Use of a depleted oil and gas reservoir, requires or redevelopment of wells and injection of CO_2 at high pressure. The mechanism for storage can be structural, residual trapping, and solubility. Structural or stratigraphic trapping via an impermeable upper boundary or caprock. Since CO_2 may under some conditions migrate upwards, it will stop once it reaches an impermeable boundary. Security is a function of the security of the seal.

Residual trapping occurs as the CO_2 plume moves through the reservoir, displacing formation fluids. The CO2 is trapped in pores by physical forces (capillary action). This mechanism contributes to the long-term security of injected CO_2 and is a trapping mechanism that continues to work even if a seal fails. Another trapping mechanism is dissolution or solubility trapping. This occurs when CO_2 dissolves into formation fluids, causing it to be trapped by geochemical means.

Existing, operational large-scale geological storage of CO_2 include the Sleipner and Snøhvit CO_2 storage projects (1.45 to 1.7 Mt- CO_2/year), the Quest project (2015), the Illinois industrial project (2017), Qatar LNG (2019) and the Gorgon project (2019). These six projects are now storing almost 10 Mt- CO_2/year in dedicated storage sites. There are also some good lessons learned from Sleipner and Snøhvit [75] which include changing conditions, and unexpected subsurface storage behaviours. Risks related to former oil and gas reservoirs include integrity of legacy wells which penetrate the cap rock and action of the acidic CO2 water mix on cement which is used to fix these wells.

Other risks include seismic activity. Ongoing study and monitoring during operations are imperative. Monitoring must also run for decades after closure. Remedial actions are always a possibility and must be anticipated and budgeted for. Geophysicists and engineers involved in storage projects acknowledge that the unique challenges of handling, injecting and stabilising CO_2 subsurface, requires advanced geophysical study and engineering beyond that used to identify and extract oil and gas.

Land requirement - For offshore reservoir storage, the only land use will be around the terminal when the offshore pipeline connects to the onshore pipeline. Much of this will be removed if it's a former oil and gas terminal, leaving a block valve station and possibly a manifold for gathering CO_2 from different sources. For an onshore reservoir, the land use depends on the original architecture of the field, which could be a small number of deep deviated wells drilled from one or two central locations or many shallow wells drilled from many locations over a wide area. This will be part of the evaluation criteria.

Materials - Carbon steel for flowline, Stainless steel (Chromium and Nickel) for well tubing, drilling mud for the drilling operation, cement for well-fixing casings and drilling tubulars.

Technical units - Reservoir monitoring equipment, well heads, chokes to control flow, control and monitoring equipment.

Operation (ongoing requirement, per year of operation)

Material supplies - Spares and materials for repairs and maintenance, including drilling tubulars.

Maintenance - Non-destructive testing (NDT) of pipework, repairs and maintenance of piping and drilling tubulars. Continuous measurement, monitoring and verification of the reservoir will be required.

Staffing – 10 FTEs.

Risk management - Seal penetration via wells or geological features (e.g. faults) could contribute to leakage risk. Detailed site assessment and optimised site design, Pressure management, Appropriate site operations and management measurement, monitoring and verification programmes to detect any leaks, Thorough assessment of the natural seals in the selected reservoir, Robust site management, Thorough assessment of any legacy wells, Robust site characterisation Integrated monitoring to detect subsurface and surface pressure changes, Regulation of the development, Prioritisation of natural resource development based on interaction risks and resource importance.[76]

Assure storage - Based on proof of the original oil and gas trap, continued monitoring will be required. For stratigraphic trapping, former/legacy wells will represent risks.

C.2 Saline Aquifer

Find and develop (build requirement to permanently store 1Mt of CO_2 per year)

Geological feature – CO_2 storage in saline aquifers is considered one of the most promising carbon storage methods [77], because of the abundance of this type of resource. It involves drilling into and pumping CO_2 into an underground saline aquifer. The sequestration is the same as with depleted oil and gas reservoirs, with the addition of mineral sequestration[78]. In mineral sequestration CO_2 is incorporated chemically into minerals, alkali-type minerals can bind the CO_2 in $CaCO_3$ for example. Depending on injection parameters

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[75] Norway's Sleipner and Snøhvit CCS- Industry models or cautionary tales, Institute for Energy Economics and Financial Analysis, Grant Hauber

[76] CO2 Storage Resources and their Development - An IEA CCUS Handbook

[77] Review of CO2 sequestration mechanism in saline aquifers, Ang Luo a, Yongming Li a, Xi Chen b, Zhongyi Zhu c, Yu Peng, H. Emami-Meybodi, H. Hassanzadeh, C.P. Green, et al.

[78] Convective dissolution of CO2 in saline aquifers: progress in modeling and experiments

and resource type, mineral trapping occurs on timescales ranging from minutes to millennia. These mechanisms have different risks and can coexist and change with time.

The saline aquifer is below usable freshwater dinking sources of water with many layers of impermeable rock in between. The risk and ongoing management issues are similar to the risk management for an oil and gas reservoir.

Land requirement - Land requirements will be minimal if drilling can be initiated from several surface locations.

Materials - Carbon steel for flowline, Stainless steel for well tubing, drilling mud for the drilling operation, cement for well-fixing casings and drilling tubulars. Note that, for steel, CO_2 mixed with water is corrosive, so well tubulars must be constructed using corrosion-resistant steel, such as 13Cr stainless.

Technical units – Drilling rigs, reservoir monitoring equipment, wellheads, chokes to control flow, control, and monitoring equipment.

Operation (ongoing requirement, per year of operation)

Material supplies - Spares and materials for repairs and maintenance, well tubing.

Maintenance – NDT of pipework, repairs and maintenance of piping and drilling tubulars. Continuous measurement, monitoring and verification of the reservoir will be required.

Staffing – 10 FTEs. Depending on the extent of new wells required.

Risk management – Detailed site assessment and optimised site design, Pressure management, Appropriate site operations and management measurement, monitoring and verification programmes to detect any leaks, Thorough assessment of the natural seals in the selected reservoir, Robust site management, Thorough assessment of any legacy wells, Robust site characterisation Integrated monitoring to detect subsurface and surface pressure changes, Regulation of the development, Prioritisation of natural resource development based on interaction risks and resource importance.

Assure storage - Monitoring will be required.

C.3 Ultramafic and basaltic formations

Find and develop (build requirement to permanently store 1Mt of CO_2 per year)

Geological feature – Again, these sequestration sites are developed by drilling into and fracturing ultramafic and basaltic formations. These are igneous rocks that can be found close to the surface in many locations around the world. CO2 is injected with water which can be fresh water or potentially seawater. This use of water is significant because the site must be close to or associated with a water source. Trapping occurs by mineralisation where dissolved CO_2 reacts with minerals in the reservoir to form solid carbonate minerals. Several pre-treatment options improve the sequestration potential of the rocks.

Land requirement - Land requirements will be minimal if drilling can be initiated from several surface locations.

Materials - Carbon steel for flowline, Stainless steel for well tubing, drilling mud for the drilling operation, cement for well-fixing casings and drilling tubulars. Note that, for steel, CO_2 mixed with water is corrosive, so well tubulars must be constructed using corrosion-resistant steel, such as 13Cr stainless.

Technical units - Reservoir monitoring equipment, water winning and purification, pumps, wellheads, flowlines, chokes to control flow, and control and monitoring equipment.

Operation (ongoing requirement, per year of operation)

Material supplies - Spares and materials for repairs and maintenance.

Maintenance - NDT of pipework, repairs and maintenance of piping and drilling tubulars. Continuous measurement, monitoring and verification of the reservoir will be required.

Staffing – 10 FTEs. Depends on the extent of new wells required.

Risk management – Detailed site assessment and optimised site design, Pressure management, Appropriate site operations and management measurement, monitoring and verification programmes to detect any leaks, Thorough assessment of the natural seals in the selected reservoir, Robust site management, Robust site characterisation Integrated monitoring to detect subsurface and surface pressure changes, Regulation of the development, Prioritisation of natural resource development based on interaction risks and resource importance.

C.4 Pipeline of 100km for CO_2 Transportation

Construction (build requirement for 100km of CO_2 pipeline)

Geological feature – N/A

Land requirement - Working width of 40m, a permanent wayleave of 10m and a compressor station site of 0.06 km2. Total land required will be ~ $1km^2$.

Materials - 45,000 tonnes of steel, assuming dense phase operation. Coatings, cathodic protection system, concrete and steel for foundations for above ground installations.

Technical units - Compression, pipeline steel, block valves every 16km, pig traps, and blowdown facilities. DAC-produced CO_2 will be relatively pure, so provided it isn't mixed with other anthropogenic sources, the minimum pressure, with some contingency, will be ~80 bar for dense phase operation.

Operation (ongoing requirement, per year of operation)

Material supplies - Carbon-free power for compression. 7MW of compression would be required to transport $MtCO_2$. Heat energy can be recovered from the compressor aftercoolers or where CO_2 is condensed using a refrigerant and pumped to pipeline pressure.

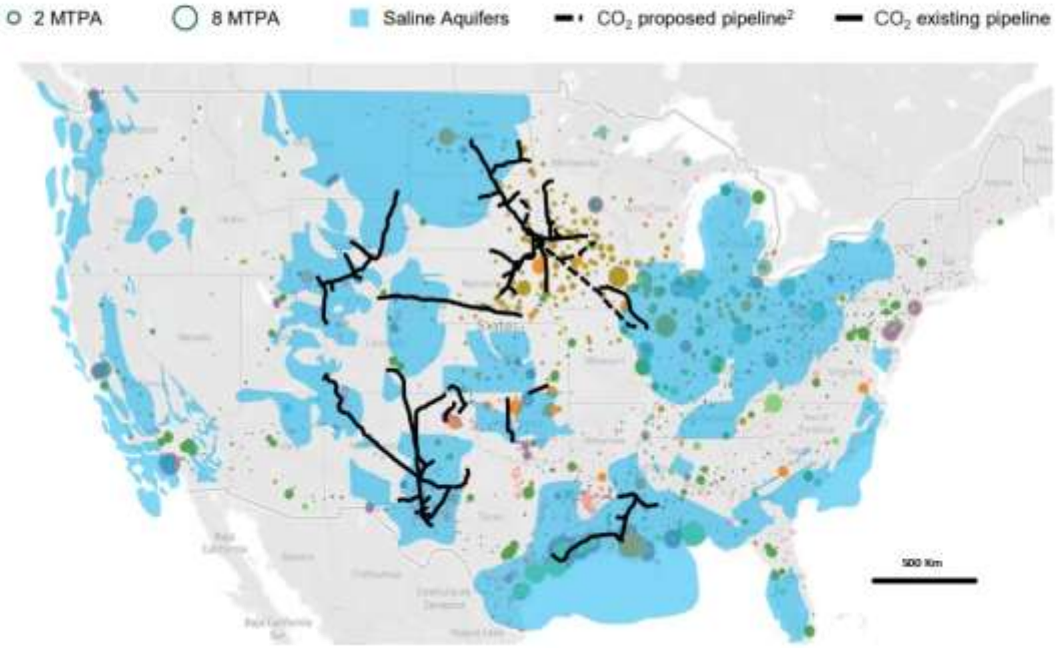
Maintenance - Intelligent pigging, surveillance, valve maintenance, NDT of piping, lubrication, vibration monitoring, ground care and maintenance.

Staffing – 20 FTEs

Risk management – Inspection, surveillance, pipeline integrity management systems, emergency preparedness, risk assessment and management.

CO2 pipeline networks exist in the USA and elsewhere, and there are plans for more,

Figure 23: Map of US CO_2 pipelines



Source: Pg 13 of US DoE, Pathways to Commercial Liftoff, 2023 link

C.5 Shipping over 1000km for CO_2 Transportation

Shipping is more economical than pipelines at distances of more than 1000km, and this mode of transport could unlock a vast choice of sequestration sites, with distances of 10,000 km+ possible.

It is likely that by 2050, much of the captured CO_2 will involve seaborne transportation and the use of many large CO_2 carriers. Currently, South Korean, and Japanese shipbuilders are proactive in developing and building carriers. The optimum pressure and temperature for CO_2 transportation is 7 bar and -50C, which is close to the triple point of CO_2. This presents very similar design conditions to that of a Liquid Petroleum Gas (LPG) carrier, which has a worldwide fleet of 800. Typically, LNG carriers have design pressures of up to 20 bar and use IMO-type C spherical or cylindrical tanks. LPG carriers transport 10,000 to 30,000 m3, compared with LNG carriers, which transport between 120 and 140,000 m^3 and Very Large Crude Carriers (VLCC), which transport 330,000 m^3.

A CO_2 ship transport system would consist of a CO_2 liquefaction plant, and intermediate insulated storage tanks (Horton spheres), Loading facilities at a port (usually a jetty), CO_2 carriers, and unloading facilities. The unloading facilities can be wholly offshore. Intermediate storage is required since CO_2 capture is a continuous process, whereas the cycle of the carrier is discreet, with one leaving every few days. Carriers could be designed to be liquid hydrogen or ammonia-powered.

The optimum energy-efficient ship speed is around 15 knots, or 28 km/h. To transport 1Mt CO_2/y 1000 km requires two 7,500m^3 CO_2 carriers, with a cycle time of 5 days, allowing for loading and unloading and 10 15m diameter intermediate storage tanks. This is very similar to the recent (2022) arrangement between Yara (fertiliser manufacturer) and Northern Lights (Norwegian CO_2 sequestration business), who have agreed to transport 800,000t, 1000 km from the Netherlands to Norway using two ships.

The advantage of using CO_2 carriers is that there is complete flexibility in the destination, which opens the possibility of a spot market for CO_2 sequestration and allows access to a CO_2 market for nations without their own storage options. 1 BtCO_2 transported globally is entirely feasible and, for example, would amount to around 500, 25,000m^3 vessels with 5-day round trips. As a comparison, currently, around 900 Mt of LNG is transported globally. The disadvantages of CO_2 transportation by ship include the requirement for access to a port and jetty and loss of CO_2 (boiloff). Storage tank boiloff is 2%, and transportation for 1000km is 1% of CO_2. The CO_2, boiloff from tanks can be re-compressed and re-liquefied but eliminating boiloff from the carrier is less practical.

An alternative way of transporting CO, by ship would be as a CO_2-hydrate. Theoretically, pure CO_2, hydrates can contain almost 30% weight CO, with the balance being water. Such hydrates are meta-stable at atmospheric pressure and slightly sub-zero temperature. This means they could be transported in bulk without pressurisation or deep refrigeration.

C.6 Permanent subsurface storage

One key difference between geological storage of CO_2, and oil and gas extraction from sometimes similar geological structures, is the need to ensure that CO_2 stays where it is intended to be. The US Environmental Protection Agency have done extensive work to develop operational checks and standards to achieve this. These can be found on the US EPA website[79], this is the key graphic.

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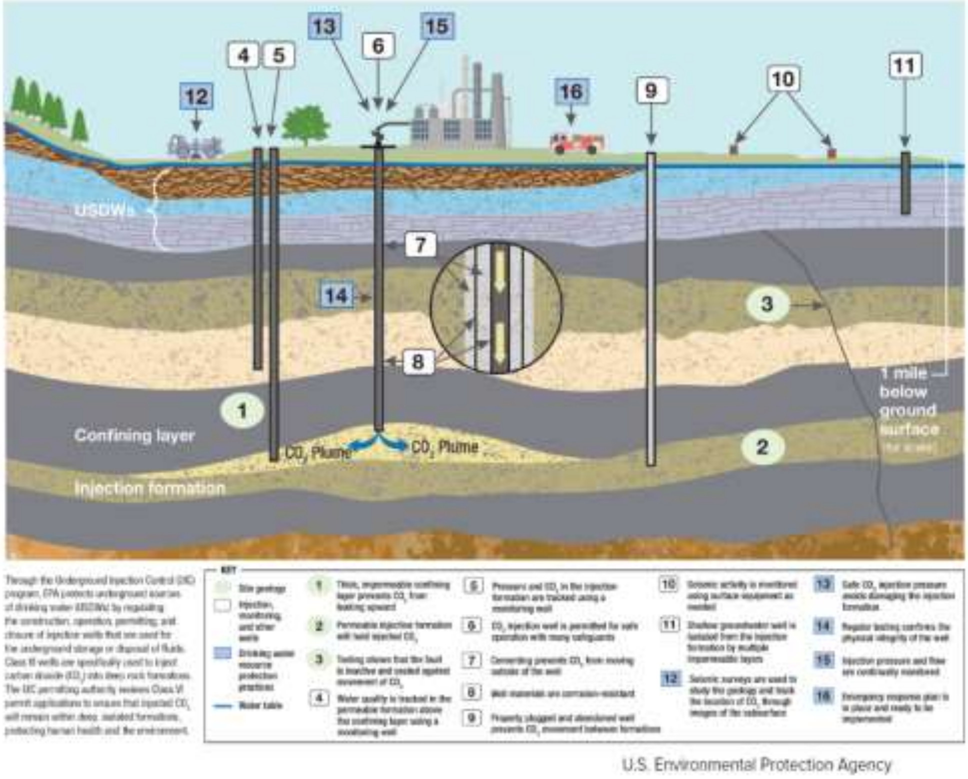
[79] Reference is epa.gov Class VI - Wells used for Geologic Sequestration of Carbon Dioxide

Figure 24: Class VI wells assurance



Source: US EPA

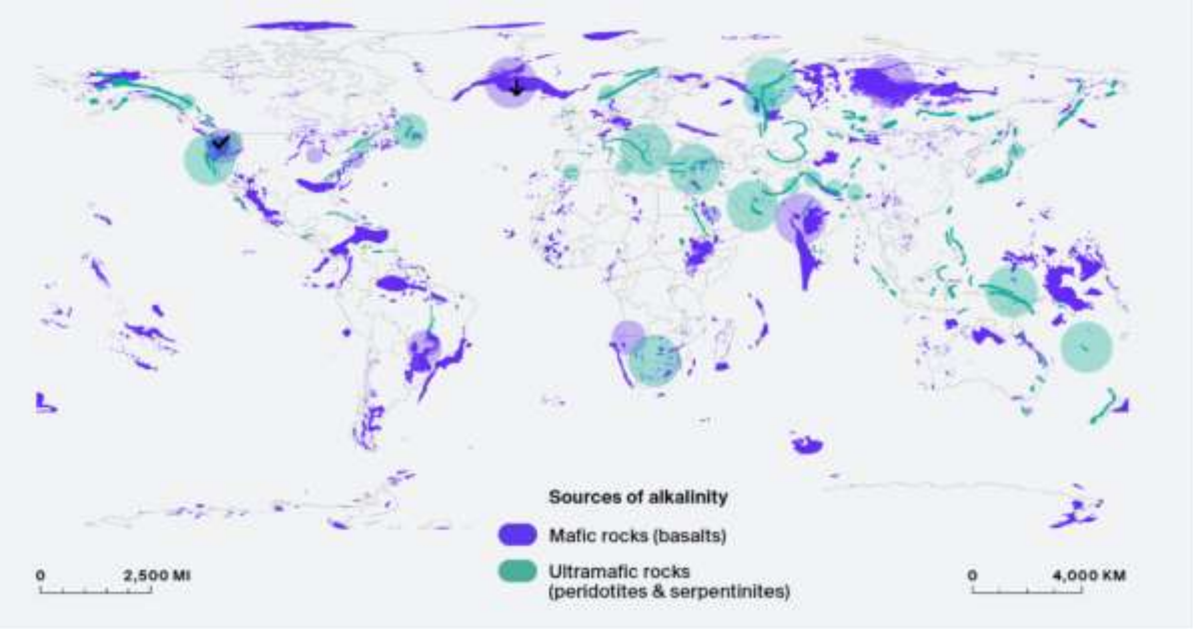
C.7 Proximity to CO_2 storage location

It’s important to be either at a potential geological storage site, be close enough to pipe CO_2 to the site, or (in the future) have efficient shipping infrastructure to transport CO_2 to a storage location.

Figure 25: Map is of thickness of sedimentary formations

Source: IEA

Figure 26: Map of basalt and ultramafic formations



Source: CDR Primer Chapter 3 figure 3.6 [link]

Note: for injection into basalts and ultramafics, water is required. For an insight into freshwater availability the rainfall map can be used (see previous section on water and humidity).