White Paper

Direct air capture: silver bullet or red herring?

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SYSTEMS AND ENGINEERING TECHNOLOGY

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INTRODUCTION

Numerous studies on the future energy mix, such as from the Intergovernmental Panel on Climate Change (IPCC), highlight the need for carbon removal technologies in order to meet the Paris Agreement targets. Limiting global average temperature to 1.5°C above pre-industrial levels (current target is 2°C by 2050) requires negative emission technologies (NETs) such as direct air carbon capture and storage (DACCS). The IPCC states "All pathways that limit global warming to 1.5°C with limited or no overshoot project the use of carbon dioxide removal (CDR) on the order of 100–1000 $GtCO_2$, over the 21st century"[(1)]. However, most predicted pathways to date have focused on BECCS (Bioenergy with Carbon Capture and Storage) or afforestation as the most viable NET technologies.

In the Energy Systems Catapult's UK pathways to Net Zero by 2050[(2)], the role of DACCS is either a limited 1 $MtCO_2$ or a speculative 25 $MtCO_2$ per year. The Committee on Climate Change's (CCCs) scenario in figure 1 shows a minor role for DACCS in removing residual UK emissions by 2050. However, DACCS is one of the greenhouse gas removal (GGR) technologies that, if proven at scale, could fill the 35 Mt void demonstrated in the scenario. As a result, the Department for Business, Energy and Industrial Strategy (BEIS) (3) has announced an innovation programme to develop these GGR technologies.

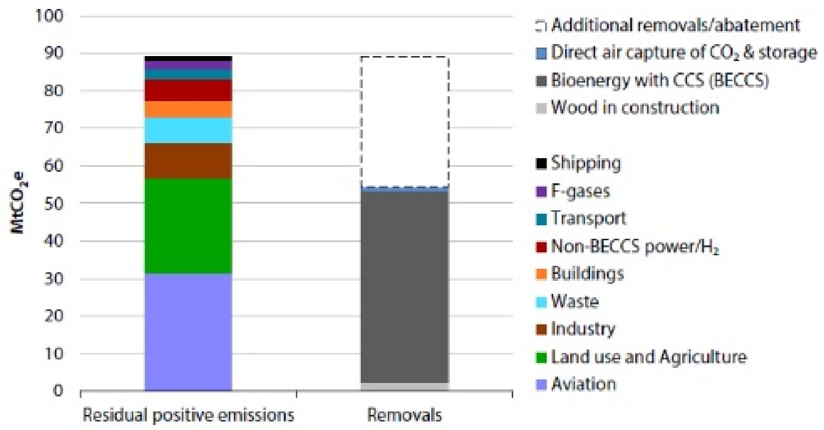
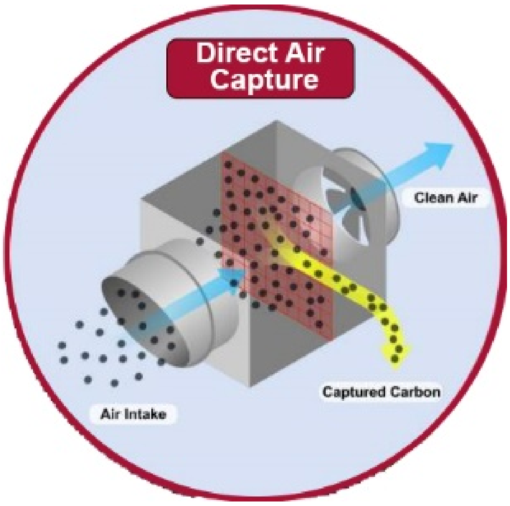


Figure 1: The CCC's "Further Ambition" Scenario[(17)]

A paper by the German Wuppertal Institute for Climate, Environment and Energy predicts a direct air capture (DAC) global market potential of 4500 $MtCO_2$/year[(4)]; whilst a study on DAC requirements in the United States[(5)] predicts a need for up to 2250 DAC plants, each capable of capturing 1 $MtCO_2$/year.

What is direct air capture?



DAC is a technology to remove the carbon dioxide (CO_2) content from ambient air. It acts as an artificial tree; however, while some of the CO_2 captured by a tree can be released into the atmosphere when it dies, all of the CO_2 captured by DAC can be permanently sequestered. DAC captures CO_2 from air and can regenerate this CO_2 for either re-use or storage purposes. The following process will focus on the chemical separation of CO_2 from air, as opposed to cryogenic (freezing CO_2 out of the air) or membrane technology (using ionic exchange and reverse osmosis membranes), both of which are not currently being considered by DAC companies (6).

- Step 1: Ambient air is directed towards the sorbent (can be enhanced using fans to pull the air through)
- Step 2: CO_2 is captured from the air via contact with a capture agent (either liquid or solid) in a similar manner to carbon capture from source (flue gas from a smokestack). Structured packing maximises contact between air and the capture medium
- Step 3: Capture agent releases "CO_2 at conditions of temperature and pressure that are accessible with low energy input, so that the capture agent can be used repetitively"[7]
- Step 4: High-purity CO_2 is compressed before transportation
- Step 5: CO_2 is utilised for other processes, such as creating plastics, chemicals, refrigerants, the food and drink industry (fizzy drinks), or as a feedstock for synthetic fuels (the current CO_2 market is 230 Mt per year[8]), or CO_2 is sequestered (permanently stored within geological formations such as saline aquifers or depleted reservoirs).

DAC captures carbon from ambient air and acts solely as a CDR technology. 'Traditional' carbon capture and storage (CCS) captures carbon from the flue gas of large industrial sources and can support the generation of an energy vector (e.g. hydrogen).

DAC concepts to date have approached steps two and three in a number of ways[4].

	Step 2		Step 3	
Concept	**Sorbent state**	**CO_2 captured by**	**CO_2 regenerated by**	**Regeneration energy needed**
A	Liquid/solution, e.g. alkaline solution such as NaOH or KOH	Absorption	Electrodialysis	Electrical
B	Liquid/solution, e.g. alkaline solution such as NaOH or KOH	Absorption	Calcination	Heat (high temperatures approx. 850°C)
C	Solid, e.g. amine-functionalised filter, amine-modified monolith, ion-exchange sorbent, porous plastic beads functionalised with benzyl-amines(7)	Adsorption (CO_2 adhering to the surface rather than being absorbed)	Desorption	Heat (low temperatures 50-100°C)

- There have been no commercial applications of concept A.
- Concept B relies on high temperatures to regenerate CO_2; thermally decomposing the precipitated carbonate.
- Either heat or heat and a vacuum desorb CO_2 from its bound state on the solid sorbent and produce a concentrated CO_2 stream in concept C. Electric heat pumps can provide a low regeneration temperature, with thermal energy storage used to balance supply and demand.

The capture sorbent is the key enabler for a working DAC system. The sorbent material considerations include its: ability to regenerate, corrosiveness or toxicity, operational costs (temperature/pressure requirements), availability (abundance), operational lifetime, humidity tolerance and scalability.

Why not just plant trees? Afforestation is a complementary GGR option; however, trees can end up competing for land space with food production, resulting in increased global food prices. 'Artificial' trees, aka manufactured DAC systems, have the advantage that they are less limited by location. DAC plants require less land than other NETs (the biomass required for BECCS has the same land issue as afforestation). A DAC plant that captures 1 $MtCO_2$/year is equivalent to the work of approximately 40 million trees requiring approximately 800,000 acres of space(9). If we crudely use the Climeworks Swiss pilot plant as an example (see table 1, below), we would require over 25,000 similar facilities in the UK to meet the Energy Systems Catapult's estimate of 25 $MtCO_2$/year and approximately 600 acres of space (not including the CO_2 transportation and storage land requirements).

In comparison with other NETs, DAC also requires far less water. "BECCS requires around 600 m3 of water for each metric ton of CO_2 removed—largely due to biomass cultivation" whilst, depending on the concept, the DACCS water requirement could be negligible up to a maximum 25 m^3/tCO_2(6). Crucially, there is ample storage capacity globally to enable storing CO_2 in geological sinks as a permanent long-term solution.

Who is advancing DAC?

There are a number of universities that include DAC technology within their CCUS research. Carbon Engineering, a leading company in DAC, was born out of Harvard University, whilst Arizona State University's Dr. Klaus Lackner played a major part in inspiring the founders of all the below companies and acts as a scientific advisor to the start-up company Silicon Kingdom Holdings (SKH).

Company	**Location**	**Scale (application)**	**Size (m^2)**	**DAC Concept**	**Desorption infrastructure (regeneration)**	**CO_2 Purity**	**Capture Rate (tCO_2 per year)**	**Current Cost ($/$tCO_2$)**	**Future predicted cost ($/$tCO_2$)**
Carbon Engineering[10], [4]	British Columbia, Canada	Pilot (fuel production)	5000	B	Temperature	99%	365	600	94-232
Climeworks[7], [6], [4]	Hinwil, Switzerland	Pilot (reuse of CO_2 in a nearby greenhouse)	90	C	Temperature or vacuum	99.9%	900	600	100
	Hellishi, Iceland (CarbFix project)	Pilot (sequestration linked to a geothermal station)	n/a				50		
	Italy (Store & Go Project)	demonstration (renewable methane production)	n/a				150		
Global Thermostat[7], [4]	California	Demonstration		C	Temperature-vacuum	99%	1000	50	15-50

Table 1 shows the status of active DAC facilities. Costs are for steps 1-3 only: excluding compression, transportation, injection, and storage costs

Carbon Engineering (CE) is the only liquid solvent-based solution in table 1, enabling a continuous process operating at steady state and needing less water than the other solutions[6]. The regeneration process of its pilot plant uses both renewable electricity and natural gas as heat sources. CE is looking to develop a purely electrical calcination process and are currently developing synthesised fuels from CO_2. During 2021, CE is aiming to begin construction of a commercial plant, capable of capturing 1 $MtCO_2$/year. This will be based in the Permian Basin during 2021, with the aim of plant rollouts globally from 2030[11].

Climeworks solution is in modular form, enabling scalability and reducing costs. It has a current capacity of 50 tons of CO_2 per 'collector' module. Whilst CE's design requires natural gas to power the system (coupled with industrial CCS), Climework's concept is powered by renewable energy and/or low-grade waste heat[12]. Its Icelandic pilot plant is powered by geothermal energy, the Italian demonstrator uses solar power, and the Swiss plant a local incinerator.

Global Thermostat claims its patented technology can be retrofitted into an existing facility, and can be used for both capture from ambient air and flue gas. It is also developing a pilot plant in Alabama to capture 4000 tCO_2/year, for reuse purposes at a global food and beverage company.

This site will use residual low-temperature heat (available at the location) as an energy source. The details of the low cost claimed in table 1 have not been made public[6].

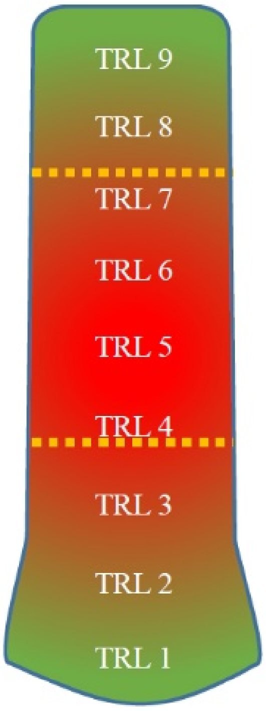
Figure 2: Artificial Tree

There are other companies entering the DAC market at a smaller scale. Infinitree is looking to utilise an ion exchange sorbent to generate CO_2 for reuse within greenhouses, whilst Skytree also proposes using a humidity swing to regenerate captured CO_2. Skytree's applications include methanol production, and scrubbing the air within a car to decrease the power needed for heating and air conditioning.

Dublin-based SKH is working with Dr Lackner to commercialise a passive direct air capture technology. The mechanical tree, unlike the three companies in table 1, will let wind alone direct ambient air towards the sorbent (no fans are proposed). Once the sorbent tiles are saturated with CO_2, the mechanical trees are lowered, and CO_2 is released from the sorbent. The process of regeneration is not clearly publicised. The pilot farm is due to be manufactured in 2021, made up of 24 mechanical trees each capable of capturing 33 tCO_2/year. If SKH's long-term view of deploying large-scale farms globally is achieved, comprising of 120,000 trees, 4 $MtCO_2$/year could be captured per farm. SKH believes it can bring the cost of capture well below \$100/tCO_2.[13]

Is DAC ready for use?

All the companies in table 1 are aiming for active megaton capacity DAC plants (capturing 1 $MtCO_2$/year) with a thirty-year lifetime, running at a viable cost of \$100/tCO_2 within the next 10-15 years. As of November 2020, no plants of this scale are in operation.



Most academic studies view DAC technology as being in the early Technology Readiness Levels (TRLs). However, Climeworks views its existing technology to be TRL-9 (technology deployed commercially)[4]. ClimateXChange's assessment (provided to the Scottish Government) puts DACCS in the TRL levels of 2-5, citing the small number of pilots and need to still prove feasibility[14]. They do not predict full operation for at least 15 years. However, if the claims by some DAC developers are realised, we are closer to full system development and deployment than that report suggests.

How much will it cost? DAC is seen as one of the most costly NETs in ClimateXChange's assessment, placing the cost in the range of \$250-700 per tCO_2 (based on exchange rates 23/10/20)[14]. More optimistic sources predict the future cost of DAC could be as low as \$50 per tonne of CO_2[4]. The energy used to power a DAC system will affect both its environmental footprint and the system running cost. The National Academy of Sciences predicts the following costs for a megaton capacity system[7].

Concept	**Fuelled by (energy source)**	**Predicted future net cost (\$/tCO_2)**
B	Natural Gas	199-357

B	Solar Photovoltaics (PV) and electrolysis H_2	317-501
C	Natural Gas	124-407
C	Solar or nuclear	89-256

None of these costs considered the use of low grade-heat for the desorption process, which has the potential to reduce total energy costs further.

How can DAC be deployed at scale?

A PESTLE analysis of the challenges facing DAC highlighted the following:

- Political. Government policy will be a key enabler/blocker to the success of DAC. Funding is most likely to be staggered as the technology matures (increased subsidies as concepts go from the research space into active deployment). Policy levers available to government include subsidising research and development (R&D), providing tax incentives to advancing DAC, taxing carbon/carbon pricing, carbon credits (e.g. certificate scheme with storage targets), and/or adapting regulation/standards to support low carbon fuels/re-use of CO_2. In the UK, BEIS has committed to provide £70 million of funding for stage 1 of its innovation programme with further funded stages planned to achieve commercial scale demonstrations in the mid-2020s[(3)]. The UKRI is also funding £31.5 million for GGR demonstrators[(15)]. In the United States, Rhodium Group (an independent research provider) recommended that the Department of Energy spend $240 million annually during the next decade on DAC R&D[(5)], whilst the recent 45Q tax credit has incentivised CCUS.
- Economic. The cost of DAC systems (due to their energy requirements) is not currently seen as viable without incentives. CO_2 in air is much more dilute than in flue gas (300 times greater compared to a coal-fired power plant)[(7)]. The more dilute a stream is, the harder it is to separate, the more energy it requires to separate, which in turn makes it more expensive. The most substantial incurred costs are in step three of the process as “significant energy costs are incurred in the step that recovers and concentrates the captured CO_2”[(7)].
- Social. As with any new infrastructure, public acceptance is not guaranteed. From a visual pollution perspective, DAC facilities can be situated almost anywhere, meaning they do not need to be near population centres or industrial sources.
- Technical. Other GGR options provide benefits in addition to removal of CO_2, DAC does not. Due to the energy intensity of the current technology, DAC must be powered by low carbon sources to be classified as a NET.
- Legal. There is a risk in prioritising the deployment of DACCS at scale at the expense of other developments. If these technologies were unable to deliver the desired reduction in CO_2, the Paris Agreement targets might not be met.
- Environmental. There are minute location and seasonal variations in the concentration of CO_2 found in air that may affect the quantity of CO_2 captured by a plant. This appears to be an area that could benefit from further research. However, from a cost and practicality perspective, the logical locations for a DAC facility would either be close to a geological storage site, near to a process requiring the use of CO_2 (e.g. a food and beverage facility), or near to an accessible low-cost heat source.

What is the future role of DAC?

Focusing on energy efficiency, developing renewables/nuclear power, and investing in ‘traditional’ CCUS remain the most viable options in reducing global warming. However, with the development of CCUS infrastructure, DAC plants could feed into the transportation and storage infrastructure. If the global carbon budget is exceeded NETs such as DAC become a necessity.

The aim of the UK’s net zero cluster approach is for areas to exist that either produce no CO_2 or offset the CO_2 that is produced by NETs (e.g. BECCS or DACCS). The current technologies being developed to capture carbon at source are aiming for efficiencies of approximately 95%: could DAC be used to capture the residual 5% and enable net zero to be achieved within a ‘cluster’? This is already being considered by Pale Blue Dot Energy which is working with CE to develop a commercial scale DAC plant potentially linked to the Acorn project’s planned cluster in the North East of Scotland(16). Alternatively, could DAC be employed in more rural areas where the concentration of industrial CO_2 sources is more sparse and ‘traditional’ CCS is not an option? As the UK looks to become a global leader in renewables, could DAC be used flexibly within the wider energy system? (e.g. using surplus clean energy for desorption when demand is lower).

DAC, to date, has focused on the capture of CO_2 from air. Methane contributes heavily to the global warming effect and is considerably more potent than CO_2; removing one molecule of CH_4 would reduce the global warming impact more than removing one CO_2 molecule. Research into this area is limited, due to methane being much less concentrated in air than CO_2 and the lack of revenue opportunity.

As is often the case, the main driver in whether DAC will be a noteworthy contributor in the GGR arena will be cost. It is for investors to judge whether this technology will be commercially viable in the future, based on their assessment of technology cost reduction and market conditions. Ultimately, DAC can be a piece of the puzzle in enabling the energy transition.

The need for a Systems Approach

From the evidence gathered, and assuming the challenges raised can be addressed as it moves up the TRLs, DAC can make a sizable contribution in reducing global emissions. Frazer-Nash Consultancy understands that there is no silver bullet to overcoming the climate change conundrum; an integrated and collaborative approach is required, which considers commercial and technical challenges. We have significant experience of analysing the development of new technologies, undertaking independent feasibility studies, supporting project and programme delivery, providing technical support, benchmarking against current best practises, and providing a roadmap for technology development.

For more info visit: www.fnc.co.uk/netzero or contact:

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