Carbon Capture, Utilisation and Storage in the Energy Transition: Vital but Limited

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Technical Annex

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Technical Annex
Contents

This technical annex is provided as a supplement to the Energy Transitions Commission's July 2022 report ***Carbon Capture, Utilisation and Storage in the Energy Transition: Vital but Limited***.[1] The document presents underlying assumptions, methodologies and wider technical details relating to materials covered in the main document. It is split into two sections:

- **Section 1** describes modelling assumptions and methodologies behind the ETC's scale up trajectory for CCUS from 2020-2050.
- **Section 2** provides additional technical details relating to technologies referred to in the report (including a focus on Direct Air Carbon Capture – DACC).

Note that throughout the report and this technical annex, carbon dioxide capture refers to engineered CO_2 capture solutions – i.e. emissions from industrial point sources and carbon dioxide removals. This definition does not extend to natural climate solutions – for analysis of these approaches, please see ETC (2022) *Mind the Gap: How Carbon Dioxide Removals Must Complement Deep Decarbonisation to Keep 1.5°C Alive.*[2]

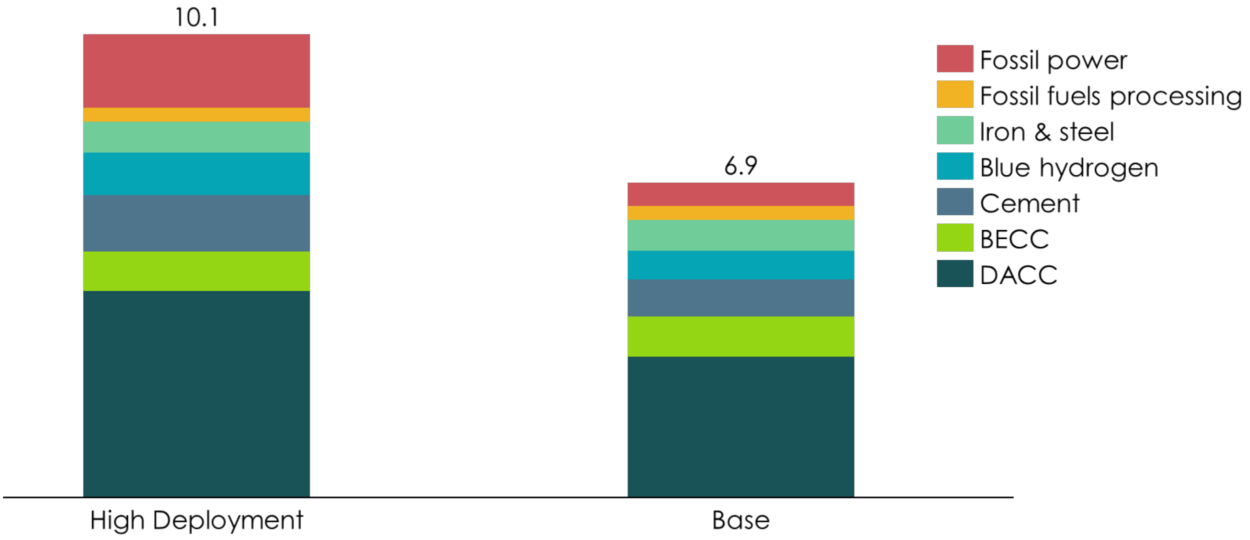
1: MODELLING ASSUMPTIONS AND METHODOLOGIES

CO_2 volumes captured to 2050

Section 1.2 of the main report presents a pathway for total CO_2 capture capacity over time on a sectoral basis: capture capacity is estimated for each sector and in aggregate. The methodology for estimating capacity varies between sectors. The same methodologies are then used for each sector to present a High Deployment Scenario and Base Scenario (Exhibit 1).[3]

Exhibit 1: Scenarios for CCUS volumes in 2050 by source of capture ($GtCO_2$/year)

EXHIBIT 1



Source: SYSTEMIQ analysis for the ETC (2022)

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[1] ETC (2022) *Carbon Capture Utilisation & Storage in the Energy Transition: Vital but Limited*

[2] ETC (2022) *Mind the Gap: How Carbon Dioxide Removals Must Complement Deep Decarbonisation to Keep 1.5°C Alive*

[3] The High Deployment scenario is based on Scenario A (incl. low energy productivity) from the ETC's Mind the Gap report. The Base Scenario is based on Scenario B (incl. higher energy productivity, and faster decarbonisation). For more details behind the non-CCUS assumptions in the ETC's scenarios see Box C of the *Mind the Gap* report.

The details of our approach for estimating carbon capture in each sector is detailed in the following sections.

Carbon dioxide removals

Bioenergy with Carbon Capture (BECC)

BECC refers to any form of bioresource (e.g. forest residues and dedicated energy crops) combustion or processing for energy purposes when used in concert with carbon capture technology (for power or heat generation, or for production of biofuels).

Estimates for BECC capacity are taken from the ETC (2021) *Bioresources within a net zero economy*, and ETC (2022) *Mind the Gap: How Carbon Dioxide Removals Must Complement Deep Decarbonisation to Keep 1.5°C Alive*.[4] Bioresources have a wide range of both energy and material applications, and can directly substitute fossil energy sources (biofuels, biogases), but sustainable supply is limited. The ETC's work in this area suggests that scarce global bioresources (around 40-60 EJ) are best prioritised towards sectors which have limited alternative decarbonisation options (e.g. aviation) or where bioenergy with carbon capture can enable carbon dioxide removals.

In total, around 870 $MtCO_2$ could be captured from BECC in 2050, of which 328 $MtCO_2$ comes from dedicated energy crops and the remainder from forestry residues. This figure does not vary between scenarios. Carbon capture at BECC plants is estimated to be around 170 $MtCO_2$/year by 2030.

Direct Air Carbon Capture

The ETC's estimate of DACC capacity over time is based on the ETC (2022) *Mind the Gap: How Carbon Dioxide Removals Must Complement Deep Decarbonisation to Keep 1.5°C Alive* and consistent with Hanna et al (2021)'s estimation of maximum plausible capacity buildout under different supply chain development pathways.[5] This models supply growth constraints based on historical precedent for similarly novel technologies. Specifically, the ETC's estimate for the High Scenario is based on a Compound Annual Growth Rate (CAGR) for DACC of 25% between 2020 and 2050, and 20% for the Base scenario. Both reach around 60 $MtCO_2$/year in 2030, with capture volumes of 4.5 $GtCO_2$/year in 2050 under the High Deployment Scenario and 3.1 $GtCO_2$/year by 2050 in the Base Scenario.

Cement

The ETC's High Deployment Scenario is based on global cement production remaining relatively stable around today's levels, declining from 4,220 Mt/year today to 4,165 Mt/year by 2050.[6] In the Base Scenario demand declines rapidly in response to significant material circularity measures, reaching 2,750 Mt/year in 2050.

We follow the IEA's Net Zero scenario in assuming the share of cement produced via CCUS reaches ~10% by 2030 and 85% by 2050. This implies around 40 $MtCO_2$/year by 2030, captured at ~30 plants (note that this includes process modifications as well as post-combustion capture technologies). By 2050, total CO_2 captured in the High Deployment Scenario reaches 1.2 $GtCO_2$/year but just 0.8 Gt CCO_2/year in Base Scenario, reflecting lower product demand (in turn owing to circular economy efficiencies).

Emissions captured refer only to process emissions – energy emissions are assumed to be decarbonised via either hydrogen or renewable energy. The cement-to-clinker ratio is assumed to decline over time from 70% today to 64% in 2050, again following the IEA.

Blue Hydrogen

Hydrogen demand varies between the High Deployment Scenario and Base Scenario, owing to variation in demand for industrial outputs such as cement, iron and steel and chemicals, which in turn rely upon hydrogen for their production. Improved efficiency and circular economy measures reduce demand for these materials in the Base Scenario relative to High Deployment, hence total hydrogen demand of 44 EJ and 64 EJ respectively.

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[4] ETC (2021) *Bioresources within a Net-Zero Emissions Economy: Making a Sustainable Approach Possible*; ETC (2022) *Mind the Gap: How Carbon Dioxide Removals Must Complement Deep Decarbonisation to Keep 1.5°C Alive*

[5] Hanna et al (2021) *Emergency deployment of direct air capture as a response to the climate crisis*. The constraints arise from how quickly supply chains and industry capabilities can scale up to deliver the maximum DACC capacity in response to the climate emergency. The parameters are based on historical examples such as the US interwar ship-building programme, roll out nuclear power in France post 1973 and solar PV growth in Germany post-Fukushima.

[6] High Deployment Scenario is based on the IEA BAU outlook for cement production (see https://www.iea.org/reports/cement) whilst Base Scenario draws Material Economics (2019) *Industrial Transformation 2050 – Pathways to Net-Zero Emissions from EU Heavy Industry*.

The split between grey, blue and green hydrogen production does not vary between scenarios. In both cases, the mix is based on the "Medium Scenario" in ETC (2021) *Making the Hydrogen Economy Possible – Accelerating Clean Hydrogen in an Electrified Economy*.[7] The CO_2 emissions intensity for blue hydrogen is fixed at 56 $MtCO_2$/EJ. The capture rate for new build increases linearly from 90% today to 95% by 2050. For retrofit, capture rates increase from 86% today to 90% in 2050.[8] Retrofitted CCS tends to deliver slightly lower capture rates owing to the need to work around existing infrastructure. New build CCS is intentionally designed as such from the outset and thus is assumed to deliver marginally higher capture rates.[9]

The methodology for deriving blue hydrogen's share of production and thus CO_2 capture is described below, with assumptions for grey retrofit and new blue hydrogen production set out in Exhibit 2.

1) Grey hydrogen retrofitting: CCS deployment within the existing stock of dedicated grey hydrogen facilities (by-product hydrogen was not considered) was modelled based on exponential application of the technology, reflecting different retrofitting speeds. This assumed:

- No new grey hydrogen plants
- Only natural gas-based hydrogen plants (71% of grey hydrogen production) were considered since the residual uncaptured emissions of a coal gasification + CCS plant were considered too high.
- All grey hydrogen plants were either retrofitted or retired by 2035.
- Plants retrofitted with CCS were assumed to extend their lifetime by 20 years from the point of retrofit.

2) Greenfield blue hydrogen: The model is based on a pipeline of projects in the last 10 years and projects announced for the next three years. A rapid acceleration of new projects was modelled reaching a plateau of new projects in 2030. This timepoint was based on the relative economics of blue/green hydrogen, which sees green hydrogen outcompeting blue hydrogen on cost over time, slowing down the blue hydrogen project pipeline beyond 2030 close to zero by 2040 (due to stranded asset risk, except in the very low-cost natural gas regions) with the same rate as the prior ramp-up.

Exhibit 2: Assumptions for "Medium Scenario" used in blue hydrogen capacity modelling

EXHIBIT 2

Scenario	Field	Assumption/Input
Retrofitting CCS to existing Grey production	Number of Plants	Gas SMR/ATR only
	Grey H_2 Stocks	Constant until 2027 then 2% retirement p.a.
	CCS Deployment	Retrofitted 1/3 by 2028. Retrofitted ~2/3 at maximum
Building new Blue production facilities	Up to 2030	Based on publicly announced pipeline (IEA database)
	Project development (compared to 2023 blue production and 2020 grey production)	2x capacity by 2028 55x capacity by 2038
	Lead time (years)	6
	Plant size (Mt/yr)	700

Source: based on inputs contained in ETC (2021) *Making the Hydrogen Economy Possible: Accelerating Clean Hydrogen in an Electrified Economy*

In total, 640 $MtCO_2$/year is captured at hydrogen production facilities in 2050 in the Base Scenario, rising to 930 $MtCO_2$/year in the High Deployment scenario. By 2030 around 120 $MtCO_2$/year is captured.

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7 ETC (2021) *Making the Hydrogen Economy Possible – Accelerating Clean Hydrogen in an Electrified Economy*
8 IPCC (2006) *Guidelines for National Greenhouse Gas Inventories*, 3.16
9 IEA (2012) *CCS Retrofit – Analysis of the Globally Installed Coal-Fired Power Plant Fleet*

Iron & Steel

The ETC estimate for CO_2 capture in the iron and steel sector is taken from Mission Possible Partnership (2021) *Net Zero Steel: sector transition strategy*. A full breakdown of assumptions and methodology used here can be found on pages 46 – 49. A summary description of the modelling methodology follows below:

- The Sector Transition Strategy model calculates pathways to net-zero emissions by 2050 for the steel sector by assessing the business case for switching to a new technology archetype each time a steel plant faces a major investment decision (e.g., relining).

- Twenty technology archetypes are considered in the model (including carbon capture technologies). Business cases for each of these archetypes consider feedstock, fuel, and energy consumption, associated emissions, and operating and capital expenditures from publicly available data sources.

- The model ensures investment decisions are made according to the criteria above, within the overall objective of reaching Net Zero by 2050 for the global steel sector.

The ETC uses the pathway generated from MPP's Technology Moratorium scenario. In this scenario, the range of technologies that can be chosen is limited from 2030 onwards to those classified as "(near-) zero-emissions" and choices are constrained by technology availability (TRL greater than 8) as well as plant relining schedules. There is no difference between the ETC's Base and High Deployment Scenarios for Iron and Steel with both scenarios capturing 10 $MtCO_2$/year by 2030, and 680 $MtCO_2$/year by 2050.

Fossil Fuels Processing & Petrochemicals

CCUS associated with fossil fuel production and processing is split into two subcategories: 1) the conversion of crude oil and natural gas into fuel products and 2) the production of high-value chemicals (HVC)[10] from either oil, natural gas or natural gas liquids.

1) Oil and Gas: CO_2 captured from the production of fuel products is, in turn, the sum of two activities: refining crude oil at refineries and stripping CO_2 from raw natural gas. Baseline oil and gas demand pathways are based on Copenhagen Economics (2017) *The Future of Fossil Fuels: how to steer fossil fuel use in the transition to a low-carbon energy system*.[11] This sees oil demand decline from ~170 EJ today to ~25 EJ in 2050 (both scenarios) and gas decline from ~110 EJ to 80 EJ or 70 EJ for scenarios High and Base scenarios respectively.

a. Oil Products: We assume gross emissions per barrel of refined crude are fixed at 40.7 $kgCO_2$/bbl (reflecting the global volume weighted average according to Jing et al (2015) *Carbon intensity of global crude oil refining and mitigation potential)*.[12] We calculate gross emissions from refining by multiplying throughput by this emissions factor. Share of refinery throughput subject to abatement is assumed to be 43% in 2030 and 99% in 2050 (based on S-Curve).

b. Natural Gas: When initially recovered from subterranean reservoirs, natural gas is typically a mixture of methane and carbon dioxide. The CO_2 must be stripped out before the gas can be sold since its presence reduces the calorific value of the natural gas and also risks pipeline corrosion. In 2020, the production of 107 EJ necessitated in ~28 $MtCO_2$ removal, implying 0.26 $MtCO_2$/EJ natural gas produced.[13] We assume this ratio remains constant over the course of the outlook – i.e. that the future discoveries of natural gas reserves will be of a similar composition to those today. Applying this ratio to the natural gas production pathway referred to above yields estimated captured CO_2 volumes.

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[10] HVC refers to Methanol, Ethylene, Propylene, Butadiene, Benzene, Toluene and Xylene.

[11] Copenhagen Economics (2017) *The future of fossil fuels: How to steer fossil fuels use in a transition to a low-carbon energy system*

[12] Jing et al (2020) *Carbon intensity of global crude oil refining and mitigation potential*

[13] IEA (2021) *About CCUS*

2) High-Value Chemicals: reliance on CCUS in the HVC sector is estimated based on demand for chemicals in the IEA's Reference Technology Scenario from (2019) *Future of Petrochemicals Report* as a baseline.[14] A series of options for decarbonising chemicals between 2020-2050 are then considered as being available to invest in over time,[15] with investments made assuming an objective to decarbonise the global chemicals sector by 2050. For further information see SYSTEMIQ and Centre for Global Commons (2022) *Planet Positive Chemicals – Pathways for the chemical industry to enable a sustainable economy*.

Demand for HVC does not vary between the two scenarios with 70 $MtCO_2$/year captured by 2030, and 140 $MtCO_2$/year captured by 2050. Demand for CCUS for gas processing lead to total CO_2 captured from fossil processing of around 170 $MtCO_2$/year by 2050 in both scenarios. Both are around 95 $MtCO_2$/year in 2030.

Power

The estimate for CO_2 capture in the power sector draws upon ETC (2021) *Making Clean Electrification Possible – 30 Years to Electrify the Global Economy*.[16] In this analysis wind and solar generation make up 75-90% of total electricity supply, with remaining electricity provided other zero carbon options, including bioenergy with carbon capture (BECC), low-carbon hydrogen, and a small role for fossil fuels with CCUS.

Coal and oil's share of the generation mix declines to zero by 2050 in High Deployment Scenario and by 2045 in Base Scenario. Gas' share declines from 24% today to 20% in 2030 and 5% in 2050 in both cases.

This leads to carbon capture of 200-400 $MtCO_2$/year in 2030 and 500-1,600 $MtCO_2$/year by 2050 across the two scenarios.

CO_2 utilisation

Section 2.5 of the main report sets out the potential for CO_2 utilisation (CCU, as opposed to Carbon Capture and Storage). The following section provides additional detail on technologies and methodologies for estimating CCU volumes. Most forms of novel CO_2 utilisation can be categorised under one of the following headings:

- **Fuel:** the utilisation of CO_2 to produce synthetic fuels such as methane or kerosene for use in conventional internal combustion engines.

- **Mineral:** converting CO_2 into solid rock via reaction with alkalines such as calcium oxide for use in building materials such as cement or aggregates.

- **Chemical:** the conversion of CO_2 into high-value chemicals such as methanol, ethylene, olefins and BTX – often as a feedstock for plastics.

An overview of the processes underpinning CO_2 utilisation in these fields, the end products and their applications are summarised in Box 1.

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[14] IEA (2019) *The future of petrochemicals*

[15] 2020: Methanol-to-olefins; 2025: Green hydrogen, CCS, gasification, methanol-to-aromatics, Hydrogen-fuelled steam cracking, Methanol-to-aromatics 2030: Direct air capture, electric steam cracking, electric steam methane reforming.

[16] ETC (2021) *Making Clean Electrification Possible: 30 Years to Electrify the Global Economy*

BOX 1

Overview of novel CCU applications

Group	Process	Description	Products	Applications
Fuel	Power to Liquids	Captured CO_2 is converted to carbon monoxide then reacted with green hydrogen	Kerosene, methanol, ammonia and other liquid hydrocarbons	Drop-in fuel in conventional combustion engine
	CO_2 Methanation (catalytic)	Reaction of cerium oxide with CO_2 in presence of ruthenium catalyst with an electric field. Requires temperature of ~100°C	Methane	Combustion for heat or power, conversion to other chemicals
Mineral	Carbon Mineralisation	CO_2 reacts with oxides or certain minerals to form carbonate	Aggregates	Concrete and other building materials production, trench pipe bedding, living rooftops
	Cement Curing	CO_2 is injected directly into liquid concrete	Cement	Concrete and other building materials
	Brining	CO_2 is reacted with magnesium chloride aqueous solution (potentially derived from waste water)	Nesquehonite	Flooring, Fireproofing, Filler Material
Chemical	Copolymerisation	Electrocatalysts containing nickel and phosphorus combine H_2O and CO_2 plastic monomers	Olefins, polymers, polycarbonates, polyols	Polyurethanes such as foams or binders

Sources: Sources: P. Schmidt et al (2018) *Power-to-Liquids as Renewable Fuel Option for Aviation: A Review*; Yamada et al (2020) *Low-temperature Conversion of Carbon Dioxide to Methane in an Electric Field*; Gomes R. (2021) *CO_2 sequestration by construction and demolition waste aggregates and effect on mortars and concrete performance – An overview*; Zhang et al (2017) *Review on carbonation curing of cement-based materials*; Glasser et al (2016) *Sequestering CO_2 by Mineralization into Useful Nesquehonite-Based Products*; Qin Y. & Wang X. (2018) *Conversion of CO_2 into Polymers*.

The methodologies underpinning CO_2 utilisation volume estimates contained in Exhibit 4 of the main report are set out below:

Enhanced Oil Recovery (EOR)

Demand for CO_2 from EOR is calculated by multiplying volumes of oil produced using EOR by a variable rate of CO_2 sequestered per unit produced (i.e. $kgCO_2$ injected per barrel of oil produced).[17] Baseline oil production is taken from previous analysis for the ETC by Copenhagen Economics,[18] declining from 100 Mb/d today to around 10 Mb/d in 2050[19] (note that this estimate is currently under review as part of the ETC's work on the future of fossil fuels). The assumed average CO_2 injected to oil recovered ratio increases from 200 $kgCO_2$/bbl in 2020 to 600 $kgCO_2$/bbl in 2050. EOR's share of total oil production increases from 0.5% today to 25% by 2050.[20]

Total CO_2 used for EOR processes is 140 $MtCO_2$/year in 2030, rising to 500 $MtCO_2$/year by 2050.

Aviation

Section 1.2.8 of the main report sets out the rationale for why synthetic aviation fuel (produced using carbon dioxide) is likely to play a key role in the decarbonisation of air travel. Bioresources are constrained by planetary boundaries; battery and hydrogen fuels are considered too low TRL for long distance. Recognising these constraints (and the need to phase out conventional fossil by 2050), demand for e-kerosene is taken from MPP (2022) *Making net zero aviation possible*, "Optimistic Renewable Electricity" scenario, from zero today to 267 Mtpa in 2050.[21]

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[17] Note that EOR is not restricted to CO2 injection – other substances such as water or natural gas may be used. However in this instance, the objective is to maximize CO_2 stored (as opposed to oil recovered) hence other substances are not utilised.

[18] Copenhagen Economics (2017) *The future of fossil fuels: How to steer fossil fuels use in a transition to a low-carbon energy system*

[19] Based on injection ratios in IEA (2019) *Can CO_2-EOR really provide carbon-negative oil? Note that all of the CO2 injected remains in place stored either as liquid or eventually becoming rock (in-situ mineralisation: see storage section of main report, Section 2.4).*

[20] IEA (2019) *Can CO_2-EOR really provide carbon-negative oil?*

[21] MPP (2022) *Making Net-Zero Aviation Possible*

Estimating how much CO_2 will be required is calculated as total e-kerosene production multiplied by a fixed rate of CO_2 required per unit e-kerosene produced. CO_2 required to produce 1 Mt e-kerosene is held constant throughout at 3.15 $MtCO_2$.

Use of captured CO_2 for synthetic aviation fuel rises to 65 $MtCO_2$/year in 2030, and to 840 $MtCO_2$/year by 2050.

High value chemicals and plastics

The main chemical synthesised from captured CO_2 is methanol, in conjunction with hydrogen which is then used to produce ethylene/propylene/benzene/xylene. Of this, around 85% are assumed to be used in the production of plastics, with the remainder used in other applications such as transportation or building materials.

Baseline demand for methanol is estimated based on the approach described for High Value Chemicals in the section above. 1.37 $kgCO_2$ is required to synthesise 1 Mt methanol.[22] We assume that 25% of total methanol production comes via recycled CO_2 by 2050.

Use of captured CO_2 for high value chemicals and plastics rises to 90 $MtCO_2$/year in 2030, and to 700 $MtCO_2$/year by 2050.

Cement

Estimated CO_2 utilisation in cement refers to curing only and does not account for CO_2 absorbed over the lifetime of the cement. Baseline demand for cement is estimated using the approach outlined earlier in this section. Assumed CO_2 utilisation rate is 21 $kgCO_2$ per cubic metre of cement produced.[23] Assumed share of cement produced utilising CO_2 curing technology increases from 0 today to 80% by 2050, leading to 6 $MtCO_2$/year being used in 2030 and 50 $MtCO_2$/year in 2050.

Aggregates

As discussed in Box 7 of the main report, carbon mineralisation via aggregates is typically more expensive than underground storage; but in some instances where transport and storage infrastructure is unavailable, utilisation in aggregates may make sense (notably in markets with limited or developing CO_2 transportation and storage infrastructure, alongside cement production with carbon capture). Given the uncertainty surrounding where such circumstances will arise, we do not model such demand for CO_2. Rather, sequestration of CO_2 in aggregates is assumed to be constrained by the availability of industrial residues, since this significantly improves the economics of carbon mineralisation by reducing gate fees for valorisation.

Key industrial residues modelled are as follows: brine, cement kiln dust, recycled concrete, steel slags, fly ash, air pollution control residues and red mud. Current volumes for all residues and CO_2 absorption rates are taken from Woodall et al (2019),[24] with the exception of red mud which comes from Silveira et al (2021).[25] Assumed share of residues utilised in carbon mineralisation increases from zero today to 35% by 2050 (this is not 100% owing to prohibitively high transport costs associated with connecting supply and demand centres).

Use of captured CO_2 for aggregates rises to 85 $MtCO_2$/year in 2030, and to 400 $MtCO_2$/year by 2050.

Total utilised CO_2 over time is shown in Exhibit 3 overleaf.

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[22] SYSTEMIQ and Centre for Global Commons (2022) *Planet Positive Chemicals – Pathways for the chemical industry to enable a sustainable economy.*

[23] Based on an average of CO_2 curing rate for building materials offered by CarbonCure – see https://www.carboncure.com/technologies/

[24] Woodall et al (2019) Utilization of mineral carbonation products: current state and potential

[25] Silveira et al (2021) *Red Mud from the Aluminium Industry: Production, Characteristics, and Alternative Applications in Construction Materials – A Review*

Exhibit 3: CO_2 utilisation over time

EXHIBIT 3

$MtCO_2$	2020	2030	2040	2050
EOR	40	140	550	490
Aviation fuels	0	60	720	840
HVC	0	30	50	100
Plastics	0	60	110	610
Cement	0	10	20	50
Aggregates	0	90	280	400
Total	**40**	**390**	**1,730**	**2,490**

Source: SYSTEMIQ analysis for the ETC (2022)

2: TECHNICAL DETAILS & TECHNOLOGY COSTS

This section provides additional detail concerning technologies described in the main report, mainly in main report Section 2.2. It is split into four sections:

- Further details on capture technologies
- Costs of capture
- Technology readiness levels for carbon capture processes
- A deep-dive on input requirements for Direct Air Carbon Capture

Capture Technologies

This section provides additional technical detail concerning CO_2 capture technologies described in Section 2.2.1 of the main report.

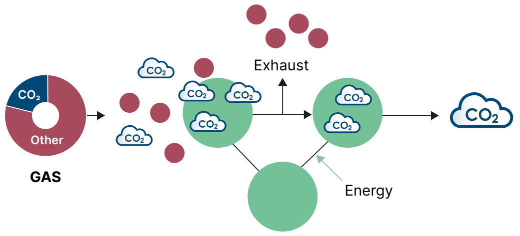
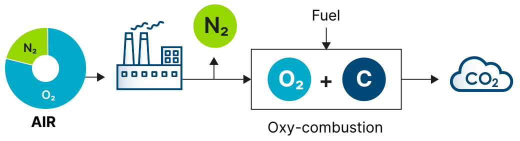
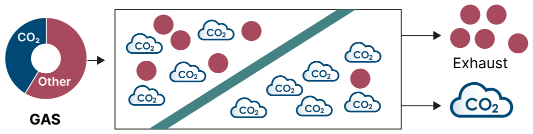
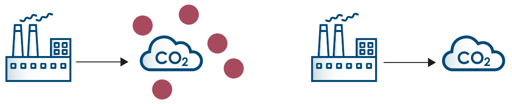
There are currently four principal systems for capturing and isolating CO_2 from point source emissions: process modification, oxy-fuel combustion, pre-combustion capture and post-combustion capture (Exhibit 4). Within these system headings, different capture technologies can be applied (sometimes the same technologies can be applied in different systems, e.g. membrane separation can be employed in both pre- and post-combustion systems). In some cases, a further subcategory of CO_2 separation techniques are worth delineating as these techniques present different TRL and cost profiles.

No one capture system, technology or technique will ever be appropriate for all situations. Different sectors present different characteristics and thus require different approaches. For example, process modifications can offer a low-cost means of isolating CO_2 from highly concentrated process emissions in cement but will not be appropriate when retrofitting power plants. Equally, individual assets' characteristics will also impact which type of carbon capture methodology is appropriate, often implying trade-offs when selecting a carbon capture system. For example, oxy-fuel combustion yields very highly concentrated CO_2, reducing costs but is more expensive than post-combustion systems to retrofit onto an existing power plant.

Given the range of sector- and asset-specifics which determine the optimal approach to carbon capture, no system or technology is ever likely to emerge as a clear "winner". Rather, different capture systems and technologies have tended to converge in specific sectors, reflecting their idiosyncrasies.

Exhibit 4: Summary of combustion technologies and systems

EXHIBIT 4

Technology type	Diagram	Description	Typical application
Solvents/Sorbents **Pre-combustion** **Post-combustion**		Gas containing CO_2 passes over reactive liquid absorbents, solid adsorbents or chemical oxide granules. CO_2 is absorbed in liquids, adheres to solids or reacts with another chemical to form a new material which is removed.	Power, chemicals, cement, iron & steel, blue H_2, natural gas processing, DAC.
Oxy-combustion		Pure oxygen is used instead of air during the combustion process producing pure CO_2 and H_2O.	Power generation, cement.
Membranes		Waste gas stream passes over a membrane which filters out nonCO_2 components.	Natural gas processing, power generation.
Process alterations		Industrial processes are altered such that waste emissions are chemically reconfigured to be pure CO_2.	Cement, some chemicals.

Source: Adapted from Bloomberg NEF (2020) *CCUS Costs and Opportunities*

Process modification

Industrial processes which release CO_2 as part of the chemical reactions inherent to the material's production can be re-engineered to generate pure CO_2 (isolated from furnace exhaust gases). This negates the need for chemical or physical separation and offers very low OPEX since the only parasitic energy in the process is CO_2 compression for transportation. Today this approach is largely restricted to cement production using the Calix process, pioneered by the Low Emissions Intensity Lime and Cement (LEILAC) project in Europe[26] and the Allam Cycle in power generation.[27]

- **Calix:** The Calix process re-engineers the existing process flows of a traditional calciner by indirectly heating the limestone via a special steel reactor. This enables pure CO_2 to be captured as it is released from the limestone, as the furnace exhaust gases are kept separate. Calcining raw meal by indirect heating (LEILAC) or by contact-heat (conventional calciner) can be done in principle with the same specific energy. The process does not involve any additional processes or chemicals, and simply involves a novel "calciner" (kiln) design.

- **Allam Cycle:** In an Allam-cycle gas fired power plant, the incoming air is stripped of everything but oxygen; that oxygen is then burned with natural gas in an atmosphere of pure, hot CO_2. The additional heat from the combustion drives the stream of CO_2 through a turbine, producing power. The heat in the exhaust gas is removed in a heat exchanger and the combustion products – water and some extra CO_2 – are taken out of the system. The same heat exchanger then heats the remaining CO_2 back up so it is ready to go through the system again. Critically, the CO_2 is isolated already so there is no need for chemical based capture. The technology has been tested at a 50 MW test facility in La Porte, Texas in 2018, owned and operated by NET Power LLC.

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[26] Hills et al., (2017) *LEILAC: Low cost CO_2 capture for the cement and lime industries*

[27] Allam et al., (2017) *Demonstration of the Allam Cycle: An Update on the Development Status of a High Efficiency Supercritical Carbon Dioxide Power Process Employing Full Carbon Capture*

Process modifications could theoretically also be extended to the iron and steel sector: the Hisarna process in which iron ore is directly converted into liquid iron does not require the preparation of iron ore agglomerates or the production of coke. In bypassing these steps, the Hisarna process can produce flue gas with very high CO_2 concentration (above 90%).[28]

Oxy-fuel combustion

Oxy-fuel combustion is the process of burning hydrocarbon fuel in a high concentration of oxygen. Like the Allam Cycle (which in part relies on oxy-combustion) the objective is to generate a pure CO_2 flue stream and therefore bypass standalone chemical or physical sorbent processes. Oxy-fuel combustion can be performed using either pure oxygen directly or as a metal oxide:

- **Pure O_2:** O_2 is pumped in as a gas, produced in an external process. The primary disadvantage of this approach is the costs associated with pure O_2 production (such as production of green hydrogen through electrolysis).[29] One potential solution is to utilise waste oxygen streams from other industrial processes.

- **Chemical Looping:** High oxygen costs can be addressed through Chemical Looping Combustion in which oxidised metals are used to supply the oxygen needed to combust fuels and then recycled back to undergo oxidation in air, reproducing the metal oxide and restarting the cycle.[30]

Pre-combustion capture

Pre-combustion capture refers to the near-complete capture of CO_2 before fossil fuel combustion and is usually implemented in conjunction with the gasification of coal or the partial oxidation of natural gas to produce synthesis gas (syngas). The syngas then undergoes a water-gas shift reaction to convert the carbon monoxide and water to H_2 and CO_2 which are then separated using one of four technologies:

- **Amine-based chemical absorption:** CO_2 is absorbed typically using amines to form a soluble carbonate salt. This reaction is reversible and the CO_2 can be released by heating the solution with the carbonate salt in a separate stripping column at pressures ranging between 1.8 and 3 bar. This process is typically associated with fossil fuel power plants, cement production and iron and steel manufacturing and is widely considered the most mature carbon capture technology.[31]

- **Physical absorption:** CO_2 is exposed to a solvent via a gas-liquid contactor, under high pressure. The solvent absorbs the CO_2 and is then transferred to a flash tank, where the pressure drops and CO_2 is released. Thus CO_2 is isolated without any chemical reaction. The process is also very mature and widely used in the production of ammonia, methanol, hydrogen, substitute natural gas, and Fischer–Tropsch products.[32]

- **Cryogenic Separation:** Cryogenic distillation is a well-established technology that achieves separation based on the different boiling points of CO_2 and other components in the gas mixture. This method is often used in natural gas purification but is also viable as a means for producing blue hydrogen or biogas upgrading. The principal drawback is the high energy requirement needed to achieve low temperatures (-100 °C to -135 °C). Costs also arise from expensive methods required to remove water vapour and limit the formation of ice / solid CO_2.[33]

- **Membranes** act as a filter, allowing CO_2 molecules to pass through whilst withholding larger molecules, thereby separating the chemicals. They can be used in pre-, post- or oxyfuel-combustion processes.[34] Membranes are generally straightforward to install since there are no additional facilities required.[35] However, the high pressure normally required can act as a cost barrier.[36]

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[28] Global CCS Institute (2017) *CCS: a necessary technology for decarbonizing the steel sector*
[29] Adams T., (2014) *Challenges and Opportunities in the Design of New Energy Conversion Systems*
[30] Pudasainee et al (2020) *Coal: Past, Present, and Future Sustainable Use*
[31] Vega F., (2018) *Solvents for Carbon Dioxide Capture*
[32] M.G. Plaza, C. Pevida, F. Rubiera, (2016) *Ongoing Activity on CO_2 Capture in the Power Sector: Review of the Demonstration Projects Worldwide*
[33] Font-Palma et al., (2017) *Review of Cryogenic Carbon Capture Innovations and Their Potential Applications*
[34] Guozhao Ji and Ming Zhao (2017) *Membrane Separation Technology in Carbon Capture*
[35] Leung, D.Y.C.; Caramanna, G.; Maroto-Valer, M.M. (2014) *An overview of current status of carbon dioxide capture and storage technologies*
[36] Scholes C., (2020) *Challenges for CO_2 capture by membranes*

Post-combustion capture

Post-combustion capture involves the removal of CO_2 from flue gas produced after the combustion of fossil fuels or other carbonaceous materials (such as biomass). This involves either an aqueous solvent (typically amine based such as monoethanolamine) or a solid sorbent (such as Zeolites, carbon-based materials or metal-organic frameworks) capturing the CO_2 and then releasing it in a vacuum, creating a pure CO_2 stream. Once separated from the CO_2, the solvent/sorbent can be recycled to capture new CO_2 molecules, although there is a limit on how many times they can be reused. Post-combustion capture technology can be applied in almost any setting and can easily be retrofitted to existing facilities since they are located at the tail-end of the process. The presence of impurities in the flue gas can however affect the subsequent CO_2 capture process (depending on the technology).

The carbon capture systems described above incur varying costs and benefits. Costs are typically a function of several interacting factors: energy requirement, installation/retrofitting costs, capture efficiency and technological maturity. These factors are described in Exhibit 5.

Exhibit 5: Carbon capture systems' advantages & disadvantages

EXHIBIT 5

Capture System	Advantages	Disadvantages
Process modification	• Low operational cost and maintenance requirement	• Potentially high CAPEX; often non-viable for retrofit • Only applicable where process yields high CO_2 partial pressure
Oxy-fuel combustion	• Fully developed, mature technology lowers mechanical failure risk • Generates near-pure CO_2, enabling wide range of capture technologies • Mass & volume of flue gas very low meaning less heat loss	• Sourcing O_2 potentially expensive if waste streams unavailable • Air separation unit (ASU) for O_2 increases power demand >15% and cost ~25% • Potentially high CAPEX for retrofit
Chemical looping	• Eliminates external O_2 input requirement	• Low TRL; complicated equipment necessary for material recycling
Pre-combustion	• High CO_2 partial pressure enhance sorption efficiency • Fully developed technology, widely commercially deployed	• Difficult to retrofit – requires chemical plant integration into process • High energy cost for sorbent regeneration
Post-combustion	• Relatively mature technology • Very easy to retrofit	• Low CO_2 partial pressure in flue reduces capture efficiency, incurring energy costs

Sources: Wang, X., Song, C. (2020) *Carbon capture from flue gas and the atmosphere: A perspective*; Leung, et al. (2014) *An overview of current status of carbon dioxide capture and storage technologies;* Herzog et al (2014) *Carbon capture and storage from fossil fuel use.*

As with capture system, capture technologies also present different characteristics, each of which carries cost implications. These are listed in Exhibit 6.

Exhibit 6: CO_2 capture systems advantages & disadvantages

EXHIBIT 6

Capture Technology	Advantages	Disadvantages
Absorption	• The most mature technology, widely used in commercial operation • High absorption efficiency (> 90% vol. CO_2) for concentrated CO_2 gas stream	• Energy intensive solvent regeneration (>120°C) incurs high costs (increasing OPEX as much as 70%)
Adsorption	• Sorbents can regenerate at lower temperatures meaning lower energy costs and allowing for sorbent recycling, reducing waste	• Relatively high material costs (solid amines) • Low selectivity of CO_2 over other gases (such as N_2, CH_4, H_2O) • Rapid decline in adsorption capacity with increasing temperature
Membranes	• Low maintenance requirement, easily installed at any stage • Low energy requirement	• Low capture efficiency at low partial pressure – requires flue gas recycling or additional membranes
Cryogenic Separation	• Mature technology, widely used in commercial applications • Extremely high CO_2 recovery rates (99.99%)	• Risk of process blockage (due to formation of ice in purification unit and/or formation of solid CO_2 on heat exchanger • High energy requirement due to extremely low temperature and high pressure employed in the process) • Large pressure drop during operation

Sources: Liu et al (2015) *CO_2 adsorption performance of different amine-based siliceous materials*; Cheng et al (2021) *CO_2 capture from flue gas of a coal-fired power plant using three-bed PSA process*; Zanco et al (2021) *Postcombustion CO_2 capture: A comparative techno-economic assessment of three technologies using a solvent, an adsorbent, and a membrane*; Leung et al (2014) *An overview of current status of carbon dioxide capture and storage technologies*; Atlaskin et al (2020) *Comprehensive experimental study of acid gases removal process by membrane-assisted gas absorption using imidazolium ionic liquids solutions absorbent*; Davison, J. (2007) *Performance and costs of power plants with capture and storage of CO_2*

Costs

A range of factors influences the cost of CO_2 capture. These include the CO_2 concentration levels in the source gas (partial pressure); capture efficiency rates (i.e. what proportion of CO_2 per unit volume is captured); energy required to capture the CO_2 (and regenerate solvents/sorbents where necessary); the scale of the plant and the minimum capture rate. The cost of capture today is principally a function of partial pressure and the TRL for the system/technology in question, which tends to favour oxy-fuel and precombustion systems alongside liquid solvent absorption technologies. However, as build-out progress and solid sorbent adsorption technologies mature, energy costs are likely to become the key price driver. In this respect, advances in electro-swing regeneration techniques point to potentially significant energy savings in the future.

CO_2 partial pressure

Of the four factors affecting total cost of capture, the main determinant is CO_2 partial pressure – the gas pressure and CO_2 concentration level in the atmosphere from which the CO_2 is captured. In the first instance, this is a function of sector (shown in Exhibit 7). However, CO_2 partial pressure is also influenced by the choice of capture system: process modifications and oxy-fuel combustion generate very high concentrations of CO_2 thereby lowering the cost of capture, relative to pre- and post-combustion systems.[37]

Exhibit 7: CO_2 partial pressure by source

EXHIBIT 7

Industrial Process	Gas Pressure (bar)	CO_2 concentration (mol%)	CO_2 Partial Pressure (bar)
Aluminium Production	1	1 to 2	0.001 to 0.002
Natural gas combined cycle power	1	3 to 4	0.03 to 0.04
Conventional coal fired power	1	13 to 15	0.13 to 0.15
Cement Production	1	14 to 33	0.14 to 0.33
Steel Production (blast furnace)	1 to 3	20 to 27	0.2 to 0.6
Hydrogen Production	22 to 27	15 to 20	3 to 5
Integrated Gasification Combined Cycle	20 to 70	8 to 20	1.6 to 14
Natural Gas Processing	9 to 80	2 to 65	0.5 to 44

Source: Husebye J. et al. (2012) *Techno economic evaluation of amine based CO_2 capture: impact of CO_2 concentration and steam supply*

The higher the CO_2 partial pressure, the lower the energy required and thus the lower the cost of capture. At the extremes, if the flue gas is near 100% CO_2 (e.g. following oxy-fuel combustion or process modification) then the cost of capture will only reflect the cost of compression. At the other end of the spectrum, DACC captures CO_2 at ambient atmospheric conditions (i.e. at the lowest naturally occurring CO_2 concentration) where CO_2 accounts for just 0.04% of total volume, implying higher cost. High partial pressure reduces costs in both CAPEX and OPEX.

- **CAPEX:** Higher CO_2 partial pressures mean that CO_2 will transfer more rapidly from the source gas to the media used to capture the CO_2, implying physically smaller capture equipment and thus reduced capital cost.[38] Higher total gas pressures also reduce the gas volume per tonne, reducing equipment size and capital cost further.

- **OPEX:** High partial pressure reduces the energy required to capture CO_2. It also allows for physical solvents as a capture medium (instead of chemical solvents) which require less energy to release the CO_2 and regenerate.[39]

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[37] Note that this does not imply process modifications or oxy-fuel systems are inherently cheaper than other systems. Other factors such as CAPEX, material input and retrofitting costs can outweigh the benefits of high partial pressure.

[38] Global CCS Institute (2021) *Technology Readiness and Costs of CCS*

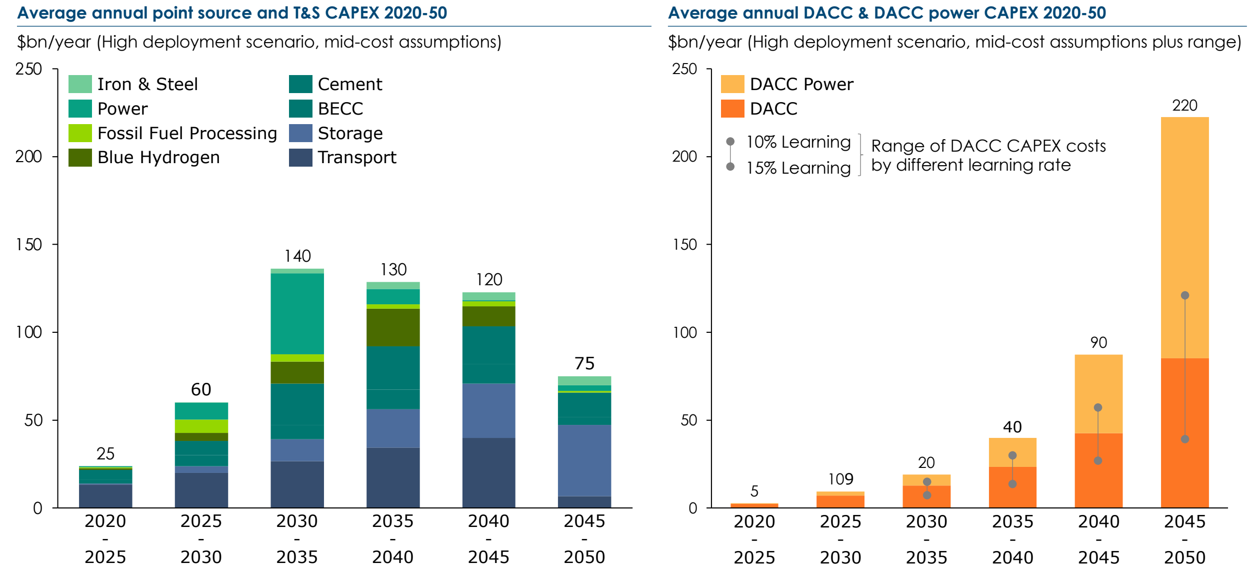
[39] Ibid

Carbon capture CAPEX

The following describes the methodology underpinning data in Exhibits 55 and 56 of the main report.

Exhibit 8: Point source and Direct Air Capture CAPEX 2020-50

EXHIBIT 8

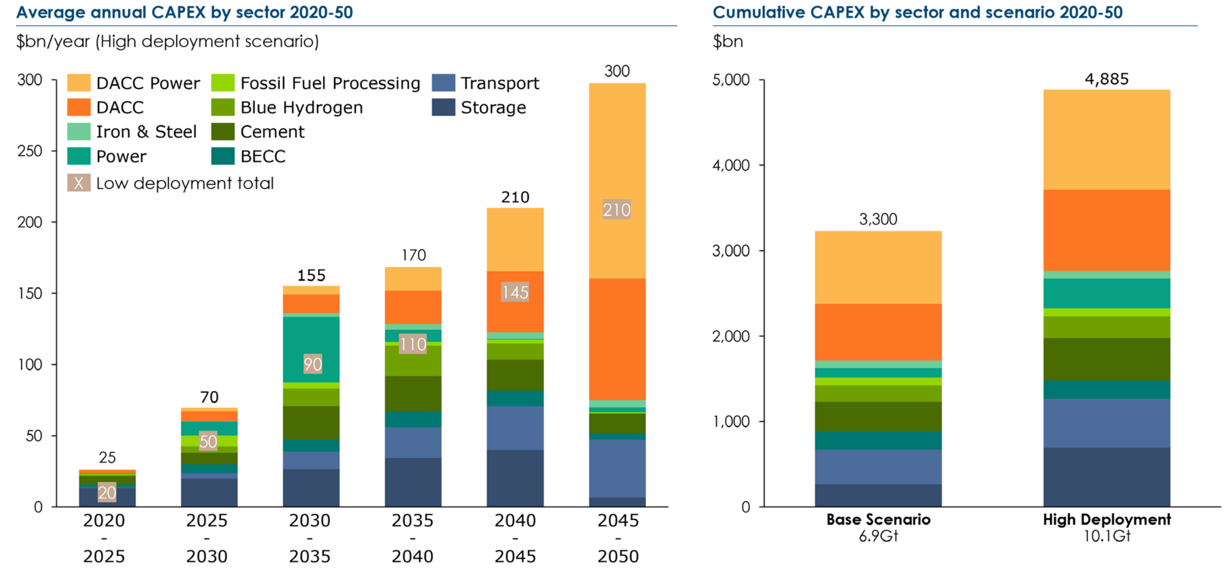


Notes: Both charts show average annual CAPEX costs for "High Scenario" in which installed capacity reaches 4.5 Gt by 2050. DACC power is shown owing to the especially high energy costs associated with collecting CO_2 from low concentration levels. For point source capture methods, energy consumption relatively trivial and is treated as an operational expenditure, therefore not shown here. DACC CAPEX bars show 12% learning rate, range indicates 15% learning (lower dot) and 10% learning rate (upper dot).

Source: SYSTEMIQ analysis for the ETC

Exhibit 9: Total and cumulative CCUS CAPEX 2020-50

EXHIBIT 9



Notes: DACC power is modelled owing to the especially high energy costs associated with collecting CO_2 from low concentration levels. For point source capture methods, energy consumption relatively trivial and is treated as an operational expenditure, therefore not shown here. High deployment Scenario refers to 10.1 $GtCO_2$ CCUS capacity by 2050 in which supply side decarbonisation measures only are deployed. Low Scenario sees 6.9 $GtCO_2$ CCS capacity by 2050 as supply side decarbonisation supported by energy productivity improvements as well.

Source: SYSTEMIQ analysis for the ETC

Annual CAPEX requirements for each sector are given by capacity additions multiplied by capital costs for that technology for that year. CAPEX costs are based on a 2020 estimate with learning rates applied for subsequent years (see Exhibit 10).

- CAPEX for each sector in 2020 is taken from Pieri (2021) with the exception of DACC (see Levelised Cost of DACC).[40]

- CAPEX requirements for each technology decline on the basis of an assumed learning rate. Learning rates for all sectors other than DACC are based on Longa (2020) and assume capital costs decline by 30% by 2050.[41]

- For DACC learning rates, we follow the IEA and assume a decline of 80% by 2050.[42] This higher rate partly reflects the fact that DACC is a newer technology and is thus still on a steeper learning curve incline. It also reflects the modular nature of solid sorbent DACC technologies (covered in more detail below).

Exhibit 10: Assumed CAPEX per tCO₂

EXHIBIT 10

	2020	2030	2040	2050
Iron & Steel	168	141	131	126
Power CCS	265	220	206	199
Fossil Fuels Processing	404	335	315	303
Blue Hydrogen	289	239	225	216
Cement	501	416	391	376
BECC	303	251	236	227
DACC	1,469	514	323	294

Source: Pieri (2021) and IEA (2022)

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[40] Pieri (2021) *Model Development for Carbon Capture Cost Estimation*
[41] Longa et al (2020) *Integrated assessment projections for the impact of innovation on CCS deployment in Europe*
[42] IEA (2022) *Direct Air Capture: A key technology for net zero*

Technology Readiness Levels

The following section adds additional detail to the topics covered in Section 3.1.1 of the main report.

The technology readiness level (TRL) of specific carbon capture technologies varies substantially, with some technologies still at prototype stage, while others have been in commercial use for years. Unsurprisingly, the capture technologies with the highest TRLs tend to be associated with sectors already operating commercial CCUS capacity. Conversely technologies at a low TRL are often best suited to capture sectors with limited CCUS uptake so far. This is illustrated in Exhibit 11 and Exhibit 12.

Exhibit 11: TRL Capture Technology by TRL and Sector

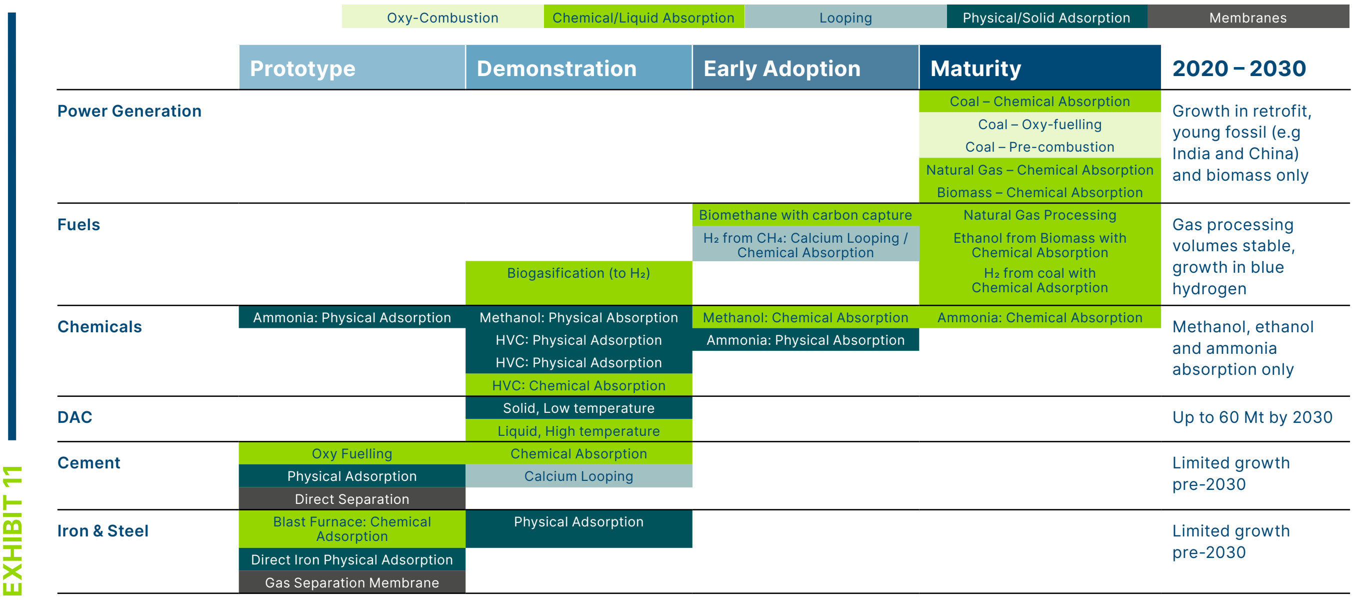


EXHIBIT 11

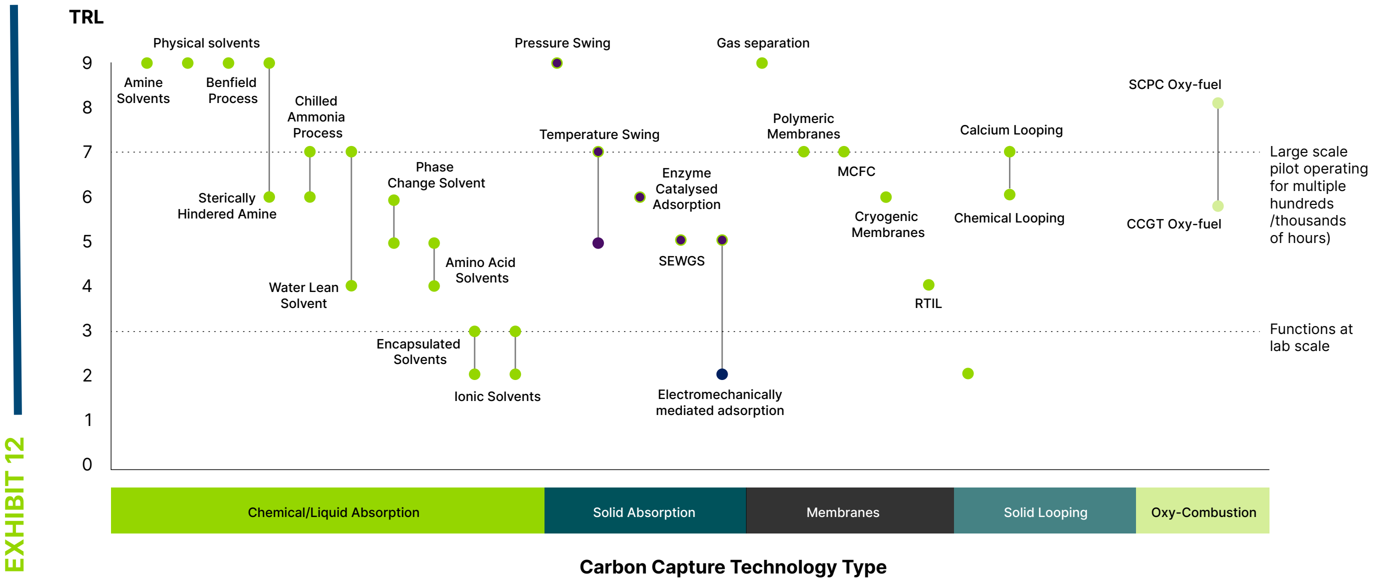
Oxy-Combustion | Chemical/Liquid Absorption | Looping | Physical/Solid Adsorption | Membranes

	Prototype	Demonstration	Early Adoption	Maturity	2020 – 2030
Power Generation				Coal – Chemical Absorption Coal – Oxy-fuelling Coal – Pre-combustion Natural Gas – Chemical Absorption Biomass – Chemical Absorption	Growth in retrofit, young fossil (e.g India and China) and biomass only
Fuels		Biogasification (to H_2)	Biomethane with carbon capture H_2 from CH_4: Calcium Looping / Chemical Absorption	Natural Gas Processing Ethanol from Biomass with Chemical Absorption H_2 from coal with Chemical Adsorption	Gas processing volumes stable, growth in blue hydrogen
Chemicals	Ammonia: Physical Adsorption	Methanol: Physical Absorption HVC: Physical Adsorption HVC: Physical Adsorption HVC: Chemical Absorption	Methanol: Chemical Absorption Ammonia: Physical Absorption	Ammonia: Chemical Absorption	Methanol, ethanol and ammonia absorption only
DAC		Solid, Low temperature Liquid, High temperature			Up to 60 Mt by 2030
Cement	Oxy Fuelling Physical Adsorption Direct Separation	Chemical Absorption Calcium Looping			Limited growth pre-2030
Iron & Steel	Blast Furnace: Chemical Adsorption Direct Iron Physical Adsorption Gas Separation Membrane	Physical Adsorption			Limited growth pre-2030

Sources: National Petroleum Council (2021) *Meeting the dual challenge: A Roadmap to CCUS deployment*; Bui M. et al, (2018) *Carbon capture and storage (CCS): the way forward*; IEA Energy Technology Perspectives (2020) *Special Report on Carbon Capture, Utilisation and Storage*

Notes: HVC = high value chemicals

Exhibit 12: Capture technologies by type and TRL



Source: Global CCS Institute (2021) *Technology readiness of CCUS*

Although there is variation in carbon capture TRLs, a majority of capture technologies necessary to hit the 2030 targets outlined in Section 3.1 of the main report are either mature or at early adoption stage today.

- The sectors expected to drive CCUS uptake in the 2020s all rely upon technologies which are already operating in commercial context. These include power generation, natural gas processing, hydrogen, methanol, biomethane and other chemicals production.

- CCUS applications currently at demonstration stage such as cement and high-value chemicals begin to exert more influence in the 2030s, reaching ~20% of CO_2 captured by 2040.

- Applications at prototype stage including DACCS, iron & steel will not emerge at significant scale until after 2030 but will likely grow rapidly thereafter.

Direct Air Carbon Capture (DACC) input requirements

The basic technique underpinning DACC is to expose a capture-medium to air at ambient conditions until a given volume of CO_2 is captured. The conditions are then changed in some way (normally temperature and/or pressure) prompting the release of the CO_2 in isolation, ready to be pressurised for onward transport – referred to as a “swing”. Since no combustion takes place, only pre-combustion technologies are currently being utilised for DACC purposes, i.e. absorption by liquid solvents (L-DACC) and adsorption by solid sorbents (S-DACC).

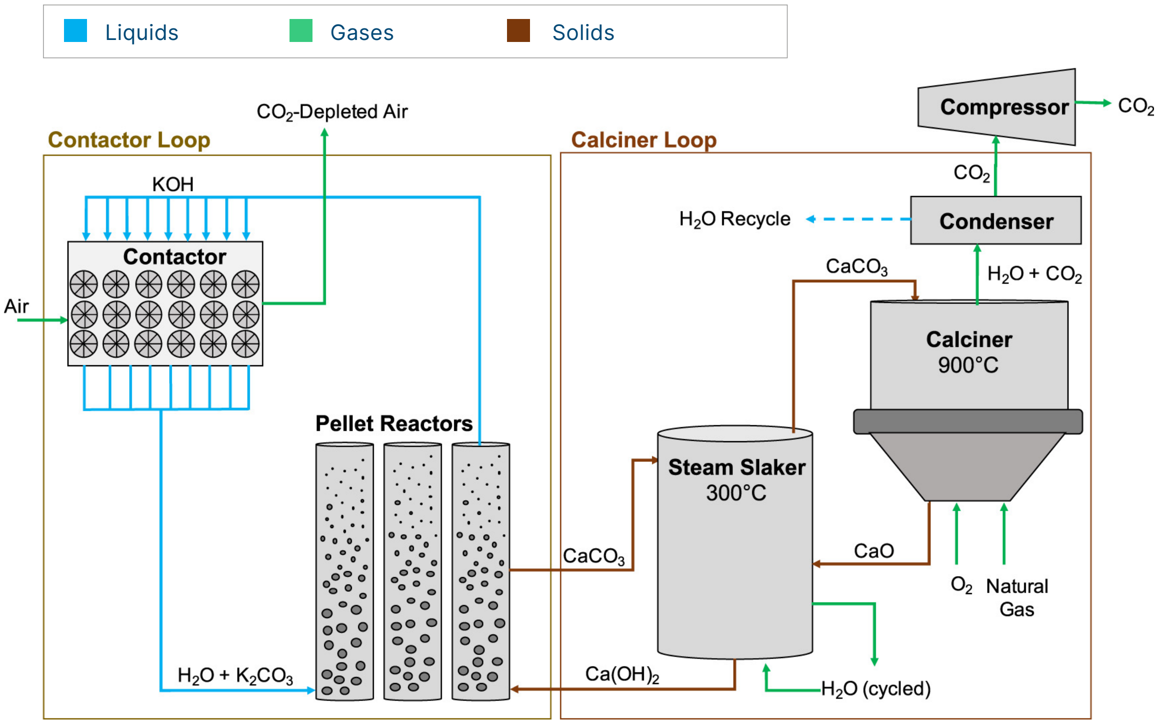
Capture Technology

Three principle processes are currently being demonstrated for DACC:

- **Liquid solvent (high temperature)** techniques are mature and have been used for many decades in natural gas processing, refining, chemicals production and food and beverage industries. The CO_2 is exposed to the solvent and is absorbed into the liquid. The solvent is then relocated and “regenerated” (i.e. the CO_2 is released) either as a result of pressure or temperature increase (known as a “swing process”). In this process:
    - ▷ Air is drawn in using fans and pumped through the capture solution via an air contactor. Potassium hydroxide (KOH, an alkali/base) flows through the contactor and reacts with the CO_2 to form K_2CO_3 solid pellets and water. K_2CO_3 is then reacted with calcium hydroxide ($Ca(OH)_2$), to swap the potassium for calcium (‘anion exchange’), forming calcium carbonate ($CaCO_3$). Sodium hydroxide, NaOH, is also viable for these first steps
    - ▷ The solid $CaCO_3$ pellets then go into the calciner loop, where they are heated up to ~900°C, in order to break them into CaO, H_2O and CO_2. This is the step that requires a lot of energy, more so than the initial ‘capture’ step.
    - ▷ Afterwards, the CaO can be hydrated to form $Ca(OH)_2$, which is then returned in order to be re-used in the anion exchange.
    - ▷ The H_2O can be released or recycled whilst the CO_2 is pressurised and transported/stored/utilised.

Exhibit 13: Representative process flow diagram of liquid (solvent) process

EXHIBIT 13



Source: McQueen et al (2021) *A review of direct air capture (DAC): scaling up commercial technologies and innovating for the future*

- **Solid sorbents (low temperature)** work in a similar manner but rather than absorb the CO_2, the molecules stick to the surface of the sorbent. Regeneration then takes place, either through heat or temperature swing or in some advanced technologies through the application of an electric current. Solid sorbents are a comparatively new technology but are considered a plausible pathway to lowering carbon capture costs (particularly for DACC) by reducing the energy required to release the CO_2 during material regeneration (owing to less evaporation of water and lower specific heat capacity).[43] This process entails:
  - Air is drawn into contact with the solid sorbent, using a fan. The sorbent adsorbs CO_2 onto its surface until saturated.
  - Once the solid is saturated, i.e. its full surface area is coated in CO_2, the fans are switched off and the unit switches to desorbing mode (i.e. releasing the CO_2).
  - The CO_2-coated sorbent is sealed off and the air inside is removed through a vacuum pump. Steam is then pumped through, increasing the temperature inside to between 80 – 100°C – this heats up the solid and removes the CO_2 (referred to as regeneration).
  - The CO_2 is pumped into the condenser, where the it is separated from the water/steam, for eventual storage.

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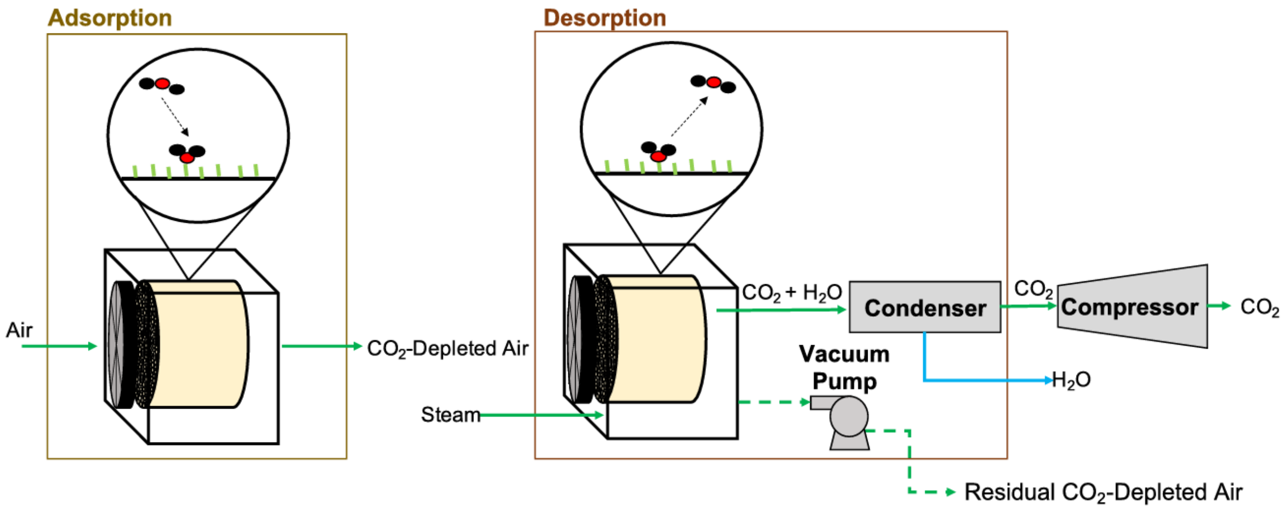
[43] Krutha et al., (2013) *Post-Combustion CO_2 Capture Using Solid Sorbents: 1 MWe Pilot Evaluation*

Exhibit 14: Representative process flow diagram of solid sorbent process

EXHIBIT 14

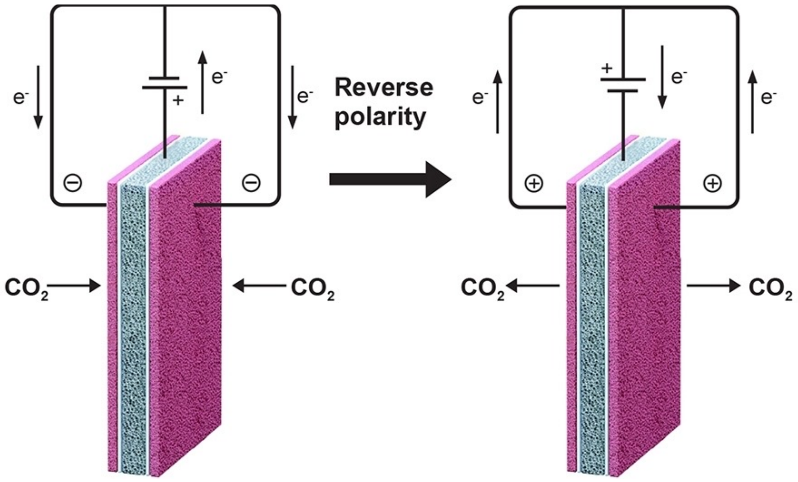


Source: McQueen et al (2021) *A review of direct air capture (DAC): scaling up commercial technologies and innovating for the future*

- **Electroswing Adsorption.** Though not yet proven at scale there is widespread expectation that electroswing adsorption (ESA) will become commercially viable in the coming decade. This technology builds on solid sorbent approaches but substitutes heat with power in the regeneration process, thereby reducing energy requirements and thus costs significantly.
    - Electrodes (such as quinones, a type of molecule) are highly ‘attractive’ to CO_2 when negatively charged.
    - By running a current through them, the quinones adsorb CO_2. When the current is reversed (‘electro-swing’) the CO_2 is released.
    - The process thus entails running a CO_2-rich stream flowing over the electrodes during charge-up, and then creating a vacuum to isolate the CO_2 during discharge. The CO_2 is then pressurised for onward storage/utilisation.
    - Low TRL materials are being explored as means to increase efficiency, e.g. coating carbon nanotubes with the quinones to increase the surface area and durability.

Exhibit 15: Representative process flow diagram of Electroswing Adsorption process

EXHIBIT 15



Source: McQueen et al (2021) *A review of direct air capture (DAC): scaling up commercial technologies and innovating for the future*

Energy requirements

Energy requirements are a function of CO_2 partial pressure and regeneration (i.e. heating the sorbent/solvent to release the captured CO_2). Low atmospheric concentration of CO_2 (0.04%) means that the energy required to bring sufficient CO_2 into contact with the capture medium is higher for DACC than for point source capture, implying higher costs. Energy used in this step accounts for around 15% of the total energy costs; the remainder is accounted for in the regeneration process.[44] Estimated energy required for both steps varies but typically ranges up to ~10 GJ/tCO_2 captured for technologies available today.

Paradoxically, the energy required to capture 1 tonne of CO_2 does not vary dramatically between solid sorbent and liquid solvent DACC, despite the difference in temperatures required to precipitate regeneration. This reflects solid DACC's comparatively low density of captured CO_2: a cubic meter of saturated liquid solvent will hold several times as much CO_2 as the same volume of saturated solid sorbent (hence the land space required to capture one tonne CO_2 via liquid DACC is ~0.4 km^2 compared to 1.5 km^2 for solid DACC). This means the volume requiring heat is much larger for soild DACC than for liquid DACC, balancing against the higher temperature requirement. Thus the energy required per tonne CO_2 captured is broadly similar, even if the intensity of the heat is much higher for liquid DACC.

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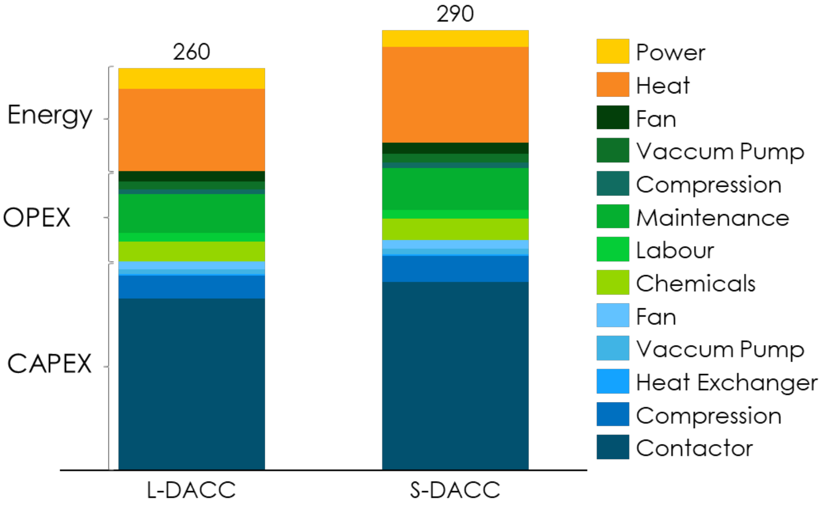
[44] National Academies of Sciences, Engineering, and Medicine (2019) *Negative Emissions Technologies and Reliable Sequestration: A Research Agenda*

Exhibit 16: Indicative DACC cost of capture 2020 ($/tCO₂)

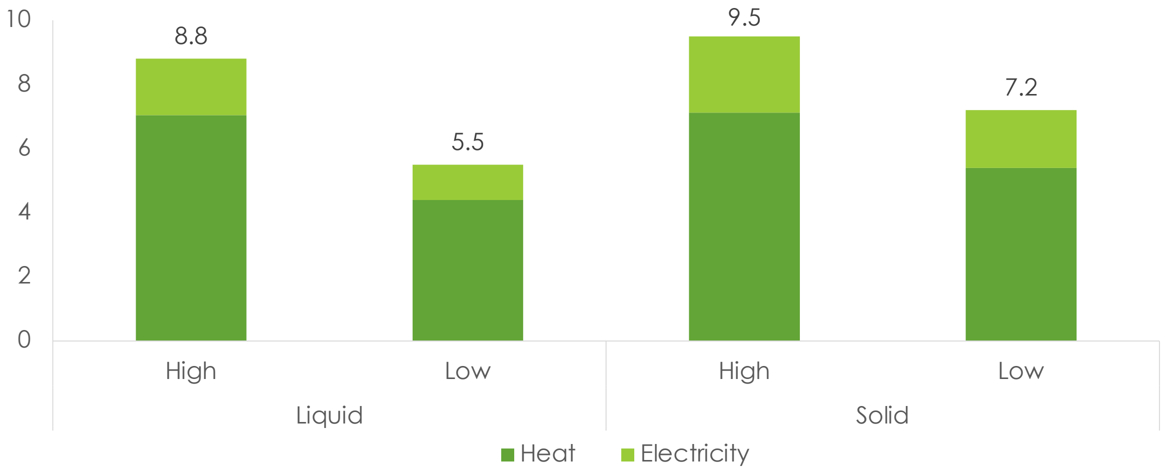
EXHIBIT 16



Sources: SYSTEMIQ analysis for the ETC; Fasihi et al (2019) *Techno-economic assessment of CO₂ direct air capture plants*; McQueen (2020) *Cost analysis of direct air capture and sequestration coupled to low-carbon thermal energy in the United States*, IEA (2022) *Direct Air Capture: A key technology for net zero.*

Exhibit 17: DACC energy requirements 2022 (GJ/tCO₂)

EXHIBIT 17



Source: IEA (2021) *Direct Air Capture: a key technology for net zero*

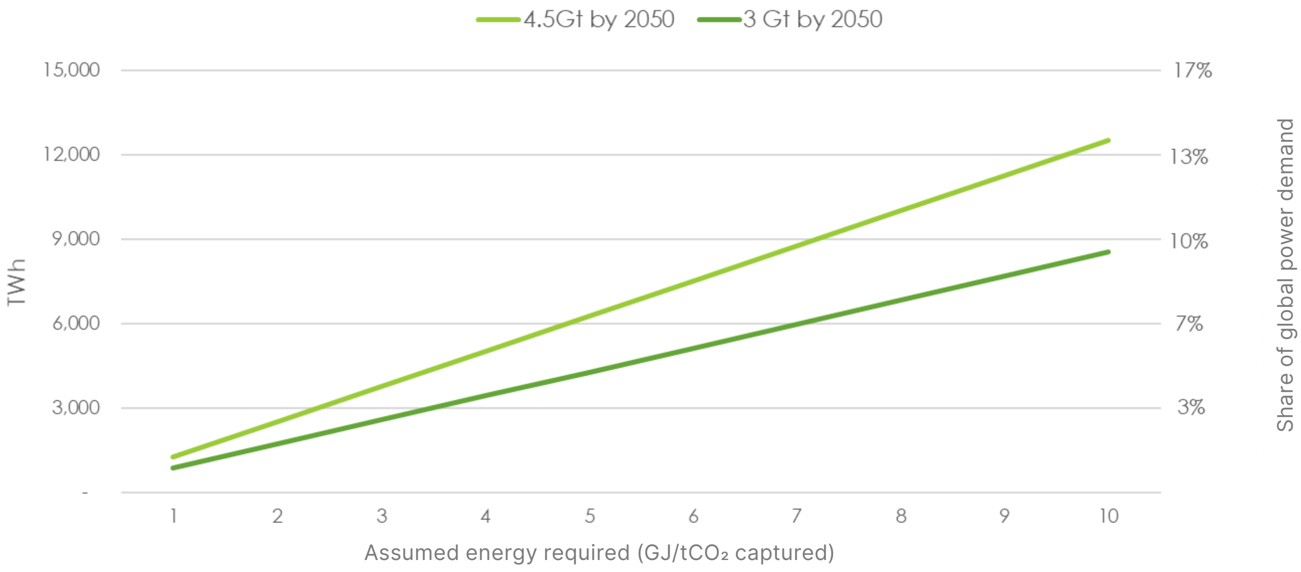
- Substantial research and investment are going into lowering the energy requirements for DACC technology today. These efforts principally focus on lowering the solvent/sorbent regeneration costs, since this is where the majority of energy requirements reside.
  - **Zeolites** are materials which can act as an adsorbent but with a vastly higher surface area per unit volume. This would reduce the space requiring heating to precipitate regeneration thus reducing costs.
  - **Electro Swing Adsorption** eliminates thermal energy requirements entirely, potentially lowering total energy requirements as low as 2 GJ/tCO₂ according to some industry projections (See Exhibit 24 of main report).

- **Membranes** have the potential to rely on a pressure differential only, eliminating energy requirements entirely, though this technique is still largely theoretical.[45]
- **Industrial hub** colocation can provide sufficient waste heat for S-DACC technologies.[46]

The uncertainty over how DACC technologies might evolve implies a wide range of estimates for energy requirements per tonne captured, potentially implying a constraint on future growth. The ETC estimates the maximum plausible DACC capacity by 2050 at between 3 – 4.5 GtCO_2 per year (varying by scenario). Exhibit 18 shows total power demand at varying energy requirements for both of these scenarios (assuming full energy requirement is met through electricity). The right-hand axis indicates DACC's share of global power demand in 2050: at the extreme, should DACC capacity approach the upper bound whilst energy requirements remain unchanged from today's levels, DACC electricity demand could exceed 12,000 TWh and global power demand could increase by more than 13%. Conversely, as energy requirements approach 2 – 3 GJ/tCO_2 captured (the range some industry participants are targeting) total power requirement is less than 3,000 TWh or a more manageable ~3% of global demand.[47]

Exhibit 18: DACC power demand by scenario in 2050

EXHIBIT 18



Source: SYSTEMIQ analysis for the ETC. Assumes all energy demand is met through power. 2050 power demand assumed to be ~90,000 TWh based on substantial productivity savings and widespread electrification.

Carbon footprint

The carbon footprint for the captured CO_2 depends on the carbon footprint of energy supply. Reliance on highly carbon-intensive power supply or natural gas to achieve sufficient temperatures offsets some of the CO_2 emissions savings, illustrated in Exhibit 19. This effect is dulled when the power is derived via industrial waste heat.

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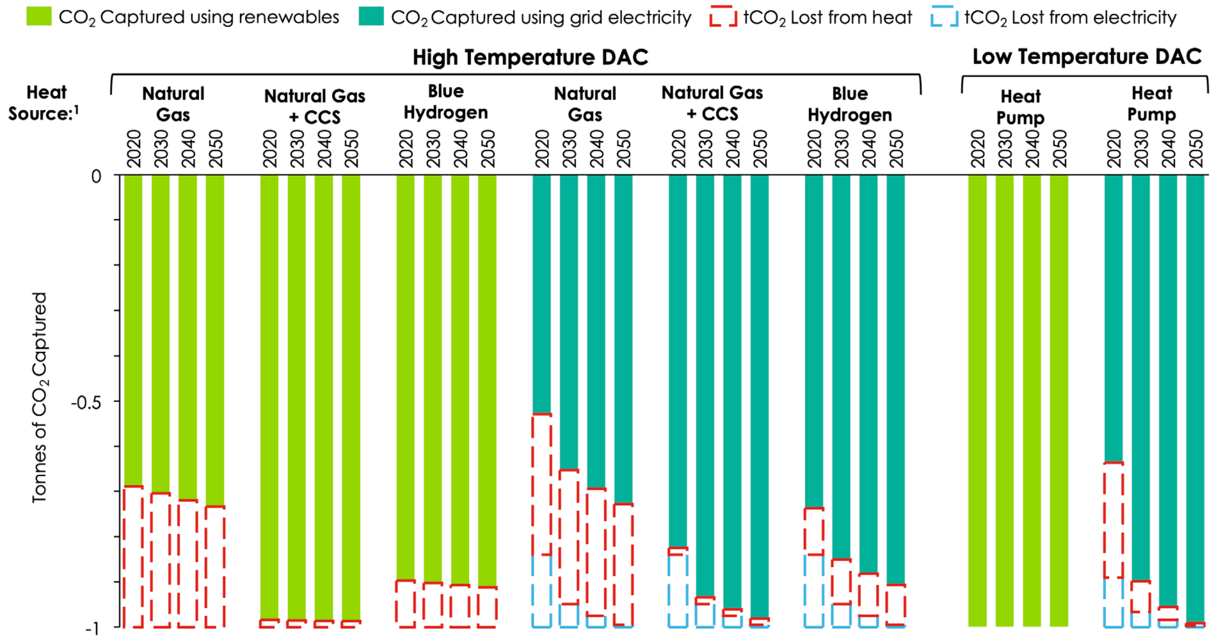
[45] Fujikawa et al (2021) *A new strategy for membrane-based direct air capture*. Note that energy is still required for compression and that the membrane will eventually need replacing, implying energy requirements here also.

[46] McQueen et al (2020) *Cost Analysis of Direct Air Capture and Sequestration Coupled to Low-Carbon Thermal Energy in the United States*

[47] This assumes a full switch to S-DACC since the temperatures required for L-DACC cannot be achieved through heat pumps or industrial waste heat alone. In the case of L-DACC, either natural gas coupled with carbon capture is required (implying high energy penalties and costs) or hydrogen (implying either carbon capture if Blue or additional renewable energy requirements if Green)

Exhibit 19: Net CO₂ Emissions from DAC, (Emissions per tCO₂ of DAC sequestered)

EXHIBIT 19

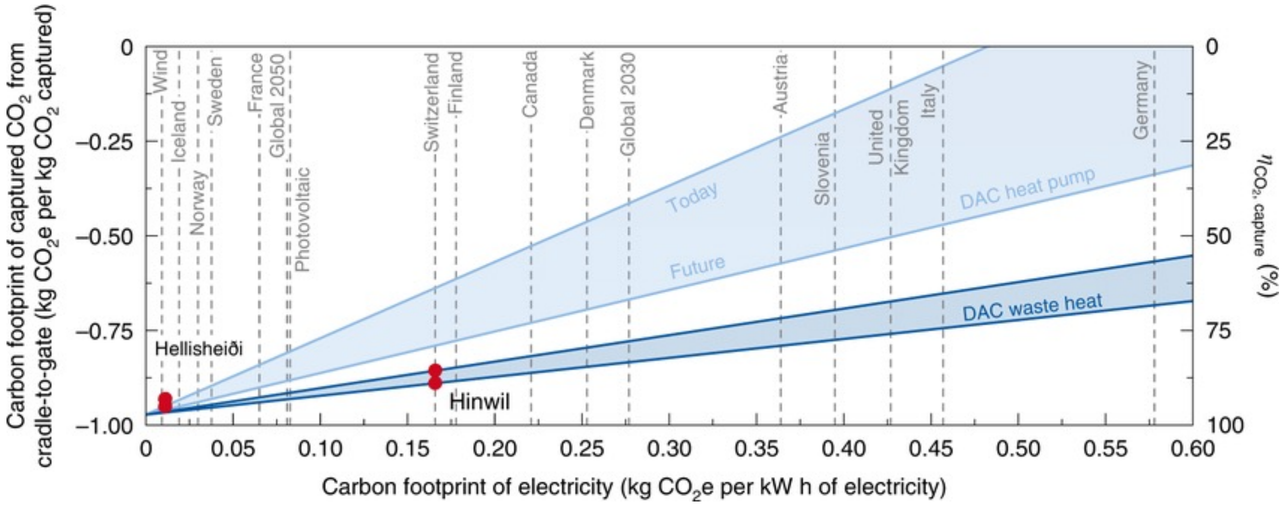


Source: Fasihi et al. (2019) *Techno-economic assessment of CO₂ direct air capture plants*

Exhibit 20 illustrates the relationship between grid carbon intensity and CO₂ capture efficiency. The dotted lines represent individual countries' grid intensities today. In regions with high grid carbon intensities (in excess of 0.45 kgCO₂/kWh) such as Italy or Germany, heat pump-powered DACC today emits more CO₂ than it captures. In the future, as energy requirements decline, DACC at these carbon intensities turns negative (although the climate benefits are still compromised). As carbon intensity approaches zero, the carbon footprint per kg of capture CO₂ reaches minus 0.90 – 0.95 kgCO₂ – the remaining emissions arise from embedded CO₂ in the materials used to build the asset.[48] DACC which relies on industrial waste heat is almost always carbon negative, regardless of the grid intensity.

Exhibit 20: Grid carbon intensity impact on DACC capture efficiency

EXHIBIT 20



Source: Deutz S. & Bardow (2021) *Life-cycle assessment of an industrial direct air capture process based on temperature–vacuum swing adsorption*

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[48] Terlouw et al (2021) *Life Cycle Assessment of Direct Air Carbon Capture and Storage with Low-Carbon Energy Sources*

Land footprint

The land footprint for DACC is smaller than the land footprint of alternative CDR approaches, especially those relying on biomass-based removal (such as afforestation). A typical liquid DACC plant requires ~0.4 km² per tCO_2 captured per annum (excluding provision of input energy needs).[49] This implies land use requirement for the DACC asset itself of between 0.1 – 0.4 million hectares (Mha) by 2050, assuming installed DACC capacity of between 3.0 – 4.5 $GtCO_2$/year.[50]

The land requirement for solid DACC is higher, ranging from 1.2 to 1.7 km², owing to the space required for ensuring sufficient sorbent surface area is exposed to the air. Assuming 1.5 km²/tCO_2 DACC capacity, solid DACC would require 0.5 – 1.4 Mha by 2050. Switching to electro-swing adsorption or zeolite sorbents could significantly reduce solid DACC's land requirement.

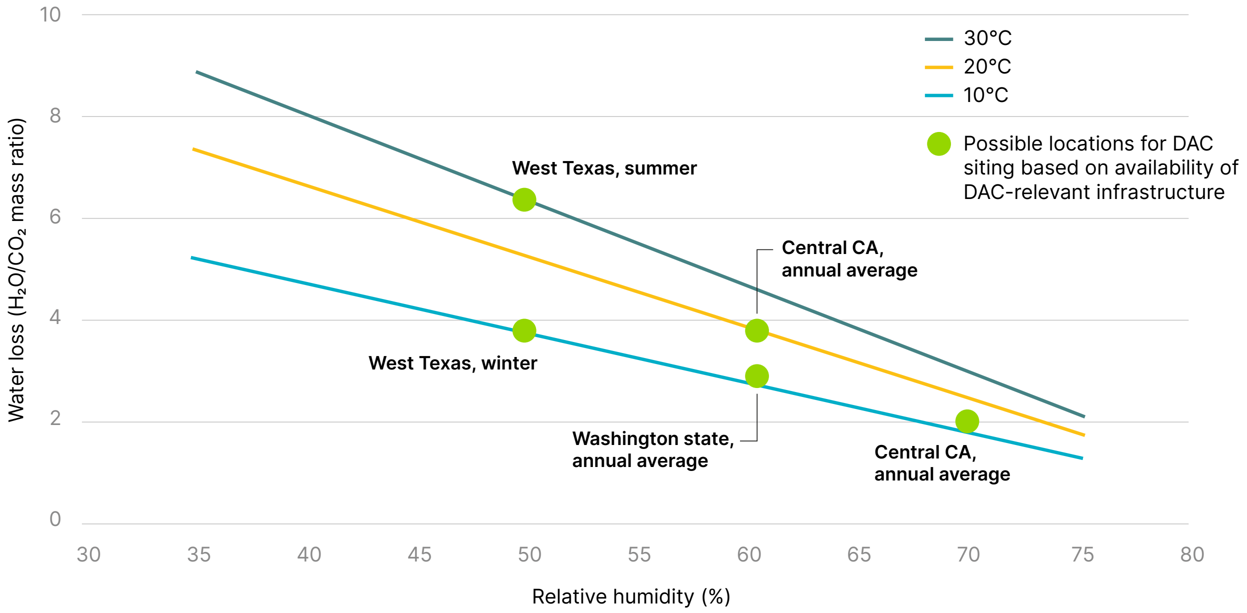
The land required to generate sufficient energy to power DACC could potentially increase total land use requirement substantially. Solar power is the most land-intensive form of power generation and thus forms an upper limit to land requirement. Assuming 1.6 ha per GWh and an energy requirement of 5 GJ/tCO_2, the land requirement would range between 6.4 – 9.4 Mha.[51] A plausible estimate for total DACC land requirement thus ranges between 6.5 – 10.8 Mha by 2050. By comparison, the ETC estimates 2,400 Mha will need to be engaged in CDR solutions by 2050 in order to deliver ~3 $GtCO_2$/year sequestration.

Water requirements

Liquid DACC typically requires between 1 – 7 tonnes H_2O per tCO_2 captured, which is comparable to the amounts of water required to produce a tonne of cement or steel.[52] The principal sources of water loss are through evaporation, hence the relative humidity and temperature of the plant's location are the main determinants of the level of water loss.[53] Water can be sourced either from natural water supply or via desalination, adding ~3–8 \$/tCO_2 to the total cost of capture.[54] S-DACC can potentially generate water, depending on humidity, implying zero water constraints.[55]

Exhibit 21: Water demand for a liquid DACC system by temperature and humidity

EXHIBIT 21



Source: Lebling et al (2021) *Direct Air Capture: Resource Considerations and Costs for Carbon Removal*

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[49] Leibling et al (2022) *6 Things to Know About Direct Air Capture*
[50] Ibid
[51] Ong et al (2013) *Land-Use Requirements for Solar Power Plants in the United States*
[52] Lebling et al (2021) *Direct Air Capture: Resource Considerations and Costs for Carbon Removal*
[53] Ibid
[54] Keith et al (2018) *A process for capturing CO_2 from the atmosphere*
[55] Fasihi et al (2019) Techno-economic assessment of CO2 direct air capture plants

Steel & cement requirements

The impact of DACC buildout on global steel and cement demand is negligible. Typical input requirements for DACC equipment today are ~4.5 kg cement and 2.6 kg steel per tCO_2 capture capacity per year.[56] In a high buildout case, this translates into 4.5 Mt cement and 2.6 Mt steel required for total asset buildout. By comparison, global cement demand in 2020 stood at 1,890 Mt and steel at 1,940 Mt.

Amine requirements

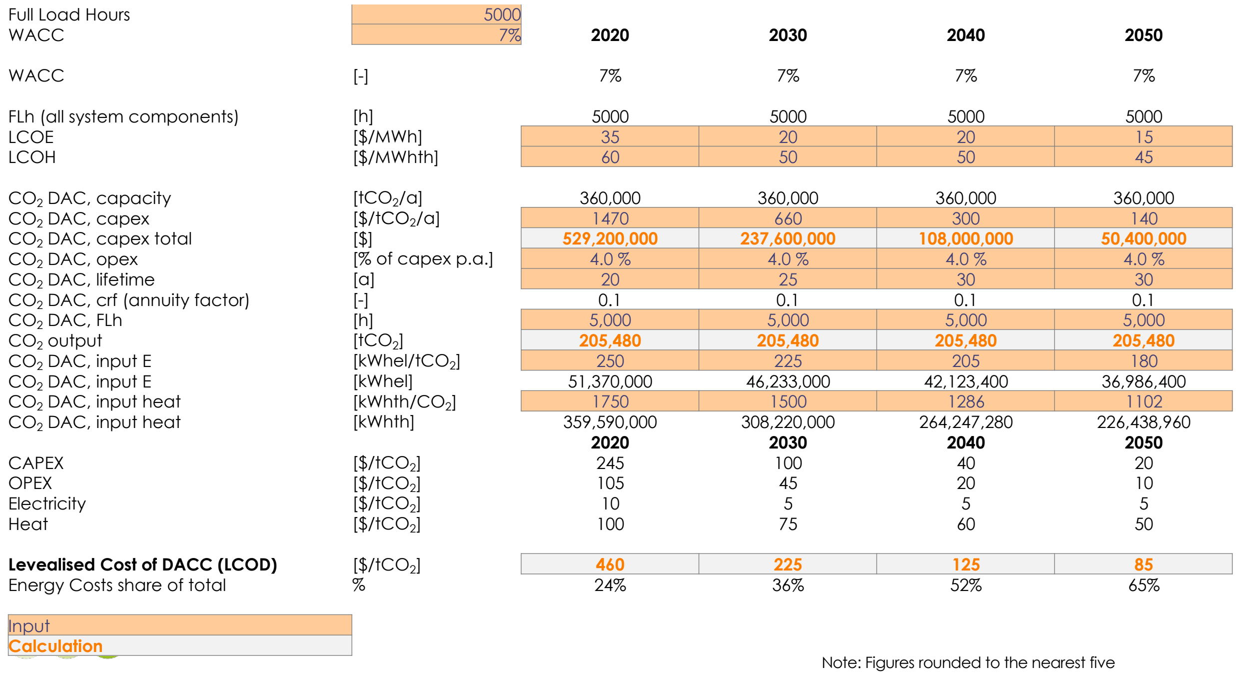
Amines are a key component in sorbents. Global production of ethanolamine was ~1,900 Kt in 2020. This figure will have to scale up to between ~10,000 – 18,000 kt/year in order to accommodate new demand from DACC. However, this expansion would still correspond to a production scale well established for polymeric materials and is not expected to be limited by the production precursors.[57] The carbon footprint arising from amines is negligible: between 10 – 50 $gCO_2/kcCO_2$ captured depending on the type of amine utilised.[58]

The levelised cost of DACC

The methodology used to estimate costs described in Exhibit 26 of the main report is as follows. We follow Fasihi et al (2019)'s Levelised cost of DACC model, using the assumptions and inputs contained in Exhibit 22.[59]

Exhibit 22: Levelised cost of DACC modelling inputs

EXHIBIT 22



Full Load Hours	5000				
WACC	7%	**2020**	**2030**	**2040**	**2050**
WACC	[-]	7%	7%	7%	7%
FLh (all system components)	[h]	5000	5000	5000	5000
LCOE	[$/MWh]	35	20	20	15
LCOH	[$/MWhth]	60	50	50	45
CO_2 DAC, capacity	[tCO_2/a]	360,000	360,000	360,000	360,000
CO_2 DAC, capex	[$/$tCO_2$/a]	1470	660	300	140
CO_2 DAC, capex total	[$]	**529,200,000**	**237,600,000**	**108,000,000**	**50,400,000**
CO_2 DAC, opex	[% of capex p.a.]	4.0 %	4.0 %	4.0 %	4.0 %
CO_2 DAC, lifetime	[a]	20	25	30	30
CO_2 DAC, crf (annuity factor)	[-]	0.1	0.1	0.1	0.1
CO_2 DAC, FLh	[h]	5,000	5,000	5,000	5,000
CO_2 output	[tCO_2]	**205,480**	**205,480**	**205,480**	**205,480**
CO_2 DAC, input E	[kWhel/tCO_2]	250	225	205	180
CO_2 DAC, input E	[kWhel]	51,370,000	46,233,000	42,123,400	36,986,400
CO_2 DAC, input heat	[kWhth/CO_2]	1750	1500	1286	1102
CO_2 DAC, input heat	[kWhth]	359,590,000	308,220,000	264,247,280	226,438,960
		2020	**2030**	**2040**	**2050**
CAPEX	[$/$tCO_2$]	245	100	40	20
OPEX	[$/$tCO_2$]	105	45	20	10
Electricity	[$/$tCO_2$]	10	5	5	5
Heat	[$/$tCO_2$]	100	75	60	50
Levealised Cost of DACC (LCOD)	[$/$tCO_2$]	**460**	**225**	**125**	**85**
Energy Costs share of total	%	24%	36%	52%	65%

Input

Calculation

Note: Figures rounded to the nearest five

Source: Fasihi et al (2019) *Techno-economic assessment of CO_2 direct air capture plants*

The asset runs for 5,000 hours per annum. The weighted average cost of capital remains constant at 7% throughout. The weighted average cost of capital is fixed at 7% throughout whilst the average plant lifetime increases from 20 years in 2020 to 30 years by 2050.

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[56] Deutz et al (2021) Life-cycle assessment of an industrial direct air capture process based on temperature–vacuum swing adsorption

[57] Ibid

[58] Ibid

[59] Fasihi et al (2019) *Techno-economic assessment of CO_2 direct air capture plants*

DACC CAPEX today is assumed to be 1,470 \$/tCO_2 per year. This is an average taken from academic and real world sources: Keith et al (2018) estimates capital costs at 1,130 \$/tCO_2,[60] Fasihi et al (2019) estimates 780 \$/tCO_2[61] and the stated CAPEX for the ORCA project, in Iceland, operated by Climeworks is 2,500 \$/tCO_2.[62]

Following Fasihi et al, we assume OPEX is fixed at 4% of CAPEX. Heat and power requirements are also taken from Fasihi – these decline as solid adsorbents replace liquid solvents as the dominant capture technology. Liquid solvent DAC systems require ~900°C to release captured CO_2, whereas solid sorbent systems require 80°C to 120°C.[63] Beyond the switch to solid adsorbents, Electro-swing technologies which seek to replace heat entirely with electricity offer even greater potential savings. Per unit energy costs are taken from BloombergNEF.[64]

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[60] Keith et al (2018) *A Process for Capturing CO_2 from the Atmosphere*
[61] Fasihi et al (2019) Techno-economic assessment of CO2 direct air capture plants
[62] Bloomberg (2021) *Inside the World's Largest Direct Carbon Capture Plant*
[63] Lebling K. (2021) *Direct Air Capture: Resource Considerations and Costs for Carbon Removal*
[64] BNEF (2022) *Data set: Cost and performance inputs for new-build power plants*