Negative Emissions Technology's Role in Achieving Net Zero

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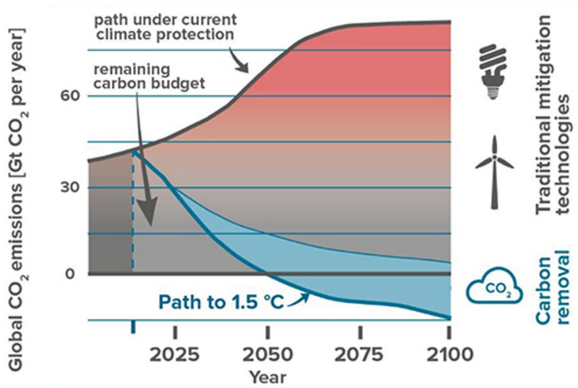
We all know about the problem: excessive anthropogenic CO_2 (greenhouse gas) emissions putting the world (and mankind) on a potentially irreversible path towards climatic disaster. The fightback is gathering steam and negative emissions technologies (including CCUS[1]) are emerging as vital tools in the pursuit of 'Net Zero'. CleanTech Capital Advisors reviews some of the most promising technologies and (humbly) evaluates their prospects.

NEGATIVE EMISSIONS AS PART OF THE SOLUTION

US former Secretary of State and current Special Presidential Envoy for Climate John Kerry controversially stated in mid-2021 that 50% of CO_2[2] reductions by 2050 will come from "technologies we don't have yet" (2050 of course being the year zero net emissions would need to reached to stay on the IPCC's[3] 1.5^{O}C pathway). Whether his prediction was correct or not, what we can say with certainty is that technology will play a vital role in achieving net zero and that consensus views have historically massively under-estimated adoption rates of 'emissions reduction' technologies (e.g. renewable energy, electric vehicles, LEDs …).

Staying Below 1.5^{O}C of Global Warming



Source: IPCC

What we also know is that a full spectrum of 'ClimateTech' – spanning alternative proteins through 'negative emissions technologies' (NET) must be pursued to have any chance of avoiding the more dire climate change trajectories. The term most synonymous with NETs is carbon capture, utilisation and storage (CCUS), whereby CO_2 is captured when or after entering the atmosphere, before being "sequestrated" and / or used.

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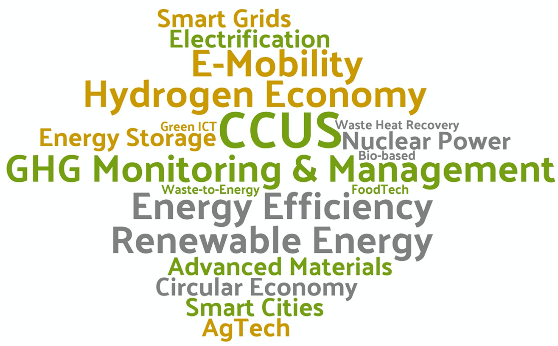
[1] Carbon capture, utilisation & storage
[2] Most references to greenhouse gases (GHG) refers specifically to carbon dioxide (CO_2), estimated to account for two-thirds of historical warming. Methane (CH_4), albeit different in nature (more potent per tonne, much shorter atmospheric duration), is estimated at 20-25% of the total.
[3] Intergovernmental Panel on Climate Change (UN)

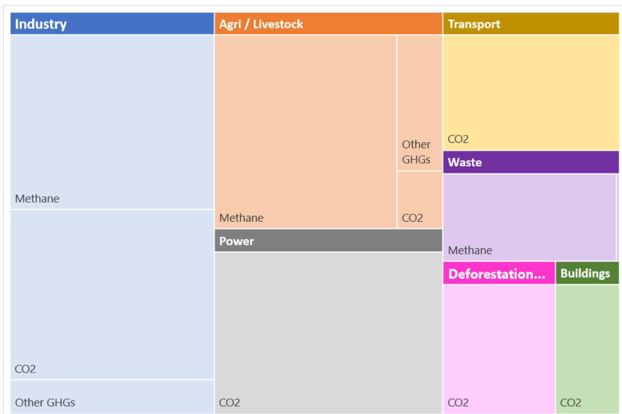
The 'ClimateTech' Arsenal



Source: CleanTech Capital Advisors

Despite efforts in earlier decades to accelerate adoption of CCUS, by the mid-2010s these efforts were largely going nowhere. However, renewed impetus since the 2015 Paris Agreement is now bearing fruit. According to the IEA, reaching net zero will be virtually impossible without **'carbon dioxide removal' (CDR) approaches (such as CCUS), which are expected to account for almost 15% of the cumulative reduction in net emissions in its Sustainable Development Scenario[4] (SDS)**.

Anthropogenic GHG Emissions by Sector & Type



Source: McKinsey (2020)

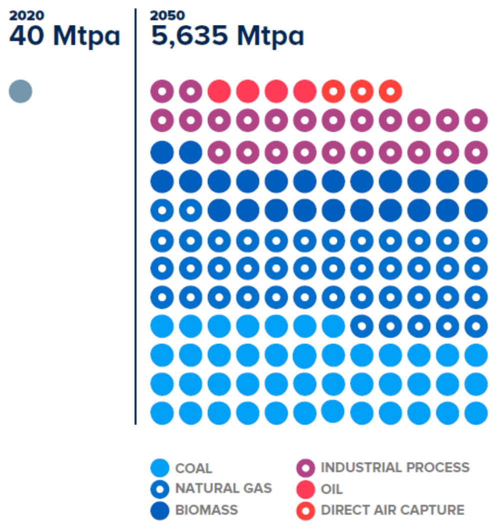
SIZING THE PROBLEM (& OPPORTUNITY)

The terminology around negative emissions can be confusing and is not always used correctly or consistently. For example, there is a not unimportant distinction to be made around **'carbon capture'** - whereby CO_2 emissions are captured at source (a point source) - and **'carbon removal'**, where the CO_2 is removed after it has already been emitted; the former can only prevent (future) emissions, whereas the latter can correct historical emissions.

Anthropogenic CO_2 emissions amounted to **43.1 gigatonnes (Gt) in pre-pandemic 2019** and, at end-2020, there was an estimated **950Gt of cumulative anthropogenic atmospheric CO_2**. It's important to remember that there are important nature-based CO_2 'sinks' (trees, soils, oceans …), though unfortunately their storage capacity is also being degraded by anthropogenic effects such as deforestation. The IPCC has said that between 100Gt and 1,000Gt of atmospheric CO_2 may need to be captured this century to avert the worst effects of climate change — far more than can be absorbed by planting more trees alone.

It is worth pointing out that "point source" technology-based carbon capture exists today (with capture efficiencies of 50%-95%); however, current global CCUS capacity is equivalent to only ~ 0.1% of annual global CO_2 emissions. The IEA's SDS projects **the amount of CO_2 captured using CCUS increasing from ~40 Mt in 2020 to ~5.6Gt in 2050** and its contribution is expected to account for 16%-90% of emissions reductions in 'hard-to-abate' sectors (e.g. iron & steel, cement, chemicals, fuel transformation, power generation).

CO_2 Capture Capacity Outlook



Source: IEA (2020)

According to the IEA, upwards of **\$160 billion will need to be spent on CCUS projects over the 2020-**

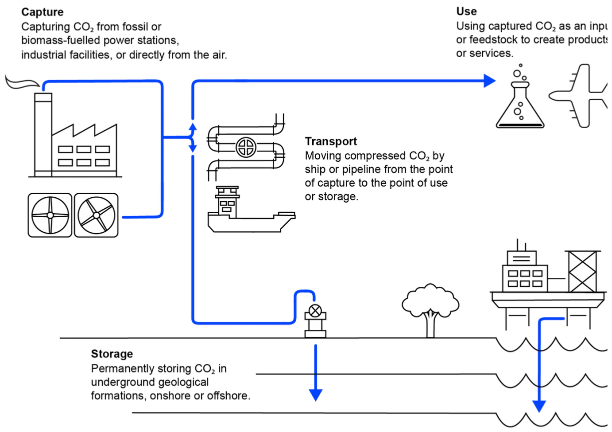
[4] Generally consistent with the Paris Agreement but prioritising universal energy access, in-line with the UN 2030 SDGs, so reaching net zero in 2070 instead of 2050.

2030 timeframe, a ten-fold increase over the previous decade.

CCUS APPROACHES

In the common use of the term – which we follow here - CCUS involves capturing CO_2 at the source (which prevents emissions from entering the atmosphere) or removing it from the atmosphere (after-the-fact) and then compressing, transporting, as well as either storing it (typically underground) or using it as an input for products. The "use" itself represents a form of storage if the CO_2 isn't, subsequent to use, "re-emitted".

Schematic of CCUS



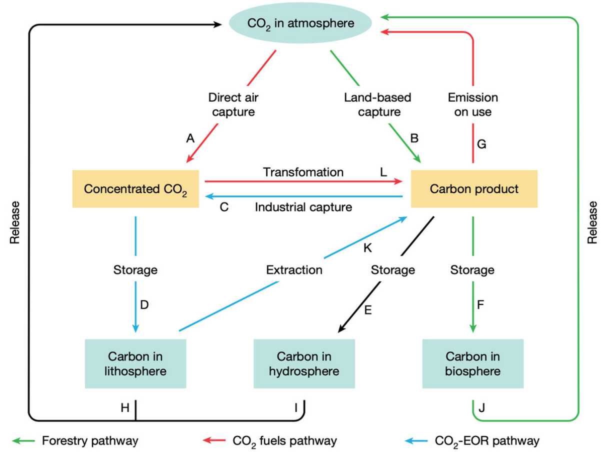
Source: IEA (2020)

Different subset terminology is often used with respect to CCUS:

- <u>Carbon capture & storage (CCS)</u>: CO_2 is captured and permanently stored ("sequestrated").
- <u>Carbon capture & utilisation (CCU) or CO_2 use</u>: CO_2 serves, for example, in the production of fuels and chemicals.
- <u>Carbon capture, utilisation & storage (CCUS)</u>: used as an umbrella term (includes CCS, CCU) and also where the CO_2 is <u>both</u> used and stored.

While generally expensive today (per tonne of CO_2 captured / removed), like other cleantech (LEDs, PV, lithium-ion batteries …), **CCUS costs are declining at around 10% pa** [*source*: The Global CCS Institute].

CCUS Technologies Pathways

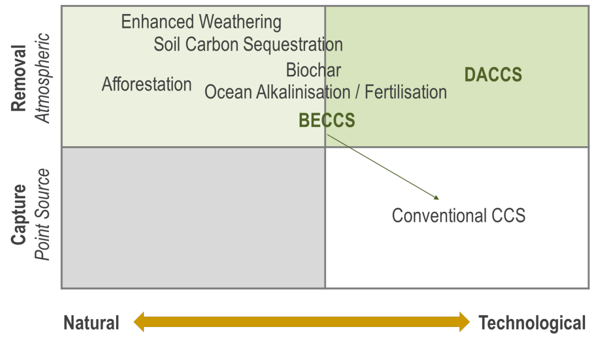


Source: Nature (2019)

CARBON CAPTURE & STORAGE

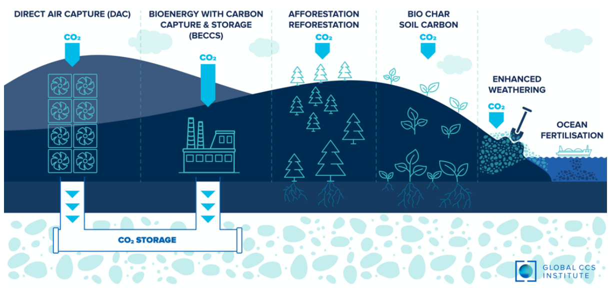
Beyond conventional point source carbon capture, the **two CCUS approaches receiving most attention today are 'bioenergy with CCS' (BECCS) and 'direct air capture' (DACS)**; the former is a hybrid nature/technology approach (see below) while the latter is purely technological. Other less covered approaches – though also with an important role to play - include soil carbon sequestration, enhanced weathering and biochar.

CO_2 Capture / Removal Options



Source: CleanTech Capital Advisors

CCUS CO_2 Flows



Source: The Global CCS Institute (2020)

<u>Bioenergy with CCS (BECCS)</u>

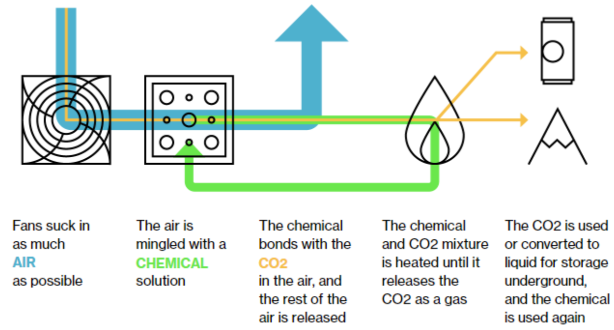
The principle of BECCS is that biomass is (already) grown and used for energy purposes. BECCS takes this to a new level in that biomass is purpose-grown specifically for CO_2 removal; as biomass is either formed, or derived, from photosynthesis, it absorbs atmospheric CO_2. The biomass is then processed into fuel, which in turn is combusted; its carbon thus forms so-called 'biogenic' CO_2, which is typically counted as a net zero emission in most GHG accounting schemes. As long as (some of) the biogenic CO_2 (in the flue gas) is captured (via conventional carbon capture) and stored/used, this represents a net reduction in atmospheric CO_2

One of the advantages of BECCS is that as the fuel from BECCS has value, this can offset the inherent cost of BECCS. BECCS is the most mature of all the carbon removal technologies, in that both bioenergy production and conventional CCS have been separately proven at commercial scale. On the other hand, the use of land / crops for BECCS represents a broader environmental trade-off.

<u>Direct Air Capture (DAC</u>

Direct air capture (DAC) technologies extract CO_2 directly from the atmosphere, for subsequent storage or use. The DAC systems operating today remove CO_2 with a liquid solvent or solid sorbent that bind CO_2 and separate it from other gases in the air. Once the capture agent is saturated, heat is applied to release the collected CO_2 and regenerate the capture agent for reuse.

DAC Schematic



Source: Bloomberg (2021)

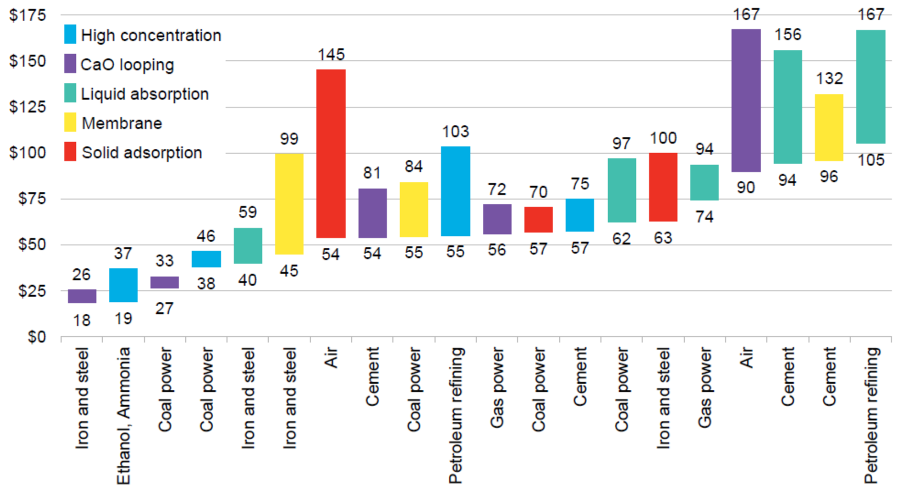
An advantage of DAC is the potential for flexibility in siting (close to inexpensive and low carbon renewable energy, CO_2 storage …) as by its nature installations don't have to be co-located with the source of the CO_2 emissions. In addition, simplistically **DAC is a one-step process**: "capture the CO_2". BECCS on the other hand involves multiple steps after the "biomass" has removed the CO_2 from the atmosphere before it is sequestrated or used. The main drawback of DAC is the low CO_2 concentration in ambient air (~400ppm, 0.04%) compared with other sources of CO_2 (flue gas has typically 4%-20% CO_2 concentration). DAC is therefore highly energy-intensive and necessitates low-carbon energy sources to provide net carbon removal. It is nonetheless an attractive technology for the most difficult-to-abate sectors / cases and can be used by large emitters in the carbon offset market.

DAC installations are generally characterised as either 'a<u>b</u>sorption' or 'a<u>d</u>sorption':

- <u>Absorption</u>: In the absorption approach the CO_2 is dissolved in a liquid (typically an amine-based solution), normally at a high temperature (~900^{O}C).
- <u>Adsorption</u>: In adsorption approaches the CO_2 adheres to the (highly porous) surface of an adsorbing substance, in a layer normally only 1-2 molecules thick. Adsorption can be achieved at relatively low temperatures (100^{O}C).

All else being equal, CO_2 capture costs are inversely related to the concentration and pressure of CO_2 in the gas stream. BECCS is generally expected to be the more prevalent CCUS approach given its relative maturity and low cost; **the IPCC puts the cost of carbon removal via BECCS at US$15-85 per tonne and that of DAC at US$250-600 / tonne**, the latter though falling relatively faster (driven by technology advances and economies of scale). The IPCC estimates that BECCS can eliminate ~11Gt CO_2 pa. The reality is that different sectors / situations have different CO_2 abatement costs, so even the most expensive CCUS approach can find its place in the market.

CO_2 Emissions Avoidance Cost at Scale (Nth-of-a-kind plants[1])



[1] kind is a cost estimate that includes the economies of scale achieved by building several identical projects
Source: BloombergNEF

CARBON TRANSPORT

After being captured and compressed, CO_2 is currently transported for storage or as a commodity product by pipeline (millions of tonnes pa), ship, road and rail. Similar to compression, CO_2 transport costs drop significantly with increasing scale. The volume of CO_2 associated with commercial CCS facilities requires transport by pipelines and/or ships, the latter generally being the lower cost option for distances of over 1,000km.

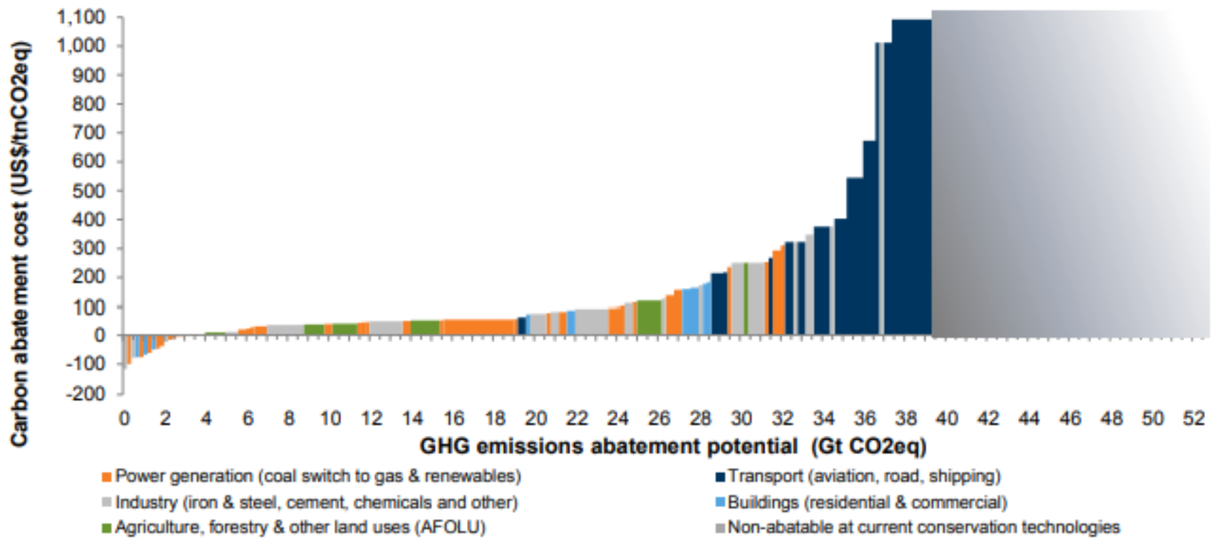
CARBON STORAGE

The storage of CO_2 is the final step in the CCS (specifically) value chain and permanently isolates CO_2 from the atmosphere. The permanence of CO_2 storage varies greatly from one utilisation pathway to another, with storage timeframes ranging from days to millennia.

The most common approach to CO_2 storage – 'geological sequestration' – involves it being stored in geological formations comparable to those which naturally contain water, oil or gas. This requires the CO_2 to be compressed to very high pressures (> 74 bar, the critical pressure of CO_2, and typically > 100 bar to provide a suitable safety margin and account for pipeline pressure drops). The storage formation must be at a depth of at least 800m to ensure that this pressure is maintained. At such high pressures CO_2 is in its "dense phase" – a density similar to water but with properties somewhere between a liquid and a gas - ensuring the efficient use of the target geological storage volume and CO_2 movement is easier to predict and monitor. Three forms of geological storage are technically mature: 1) storage through CO_2-EOR[5]; 2) storage in saline formations; and, 3) storage in depleted oil and gas fields.

[5] enhanced oil recovery

CO₂ Marginal Abatement Cost (MAC) Curve (by Sector)



Source: Goldman Sachs

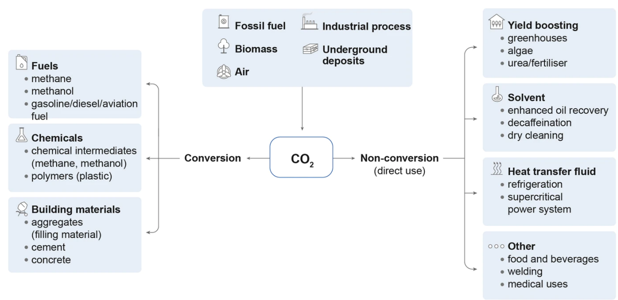
CARBON USAGE

Carbon utilisation involves CO_2 being used as a feedstock in the production of fuels, carbonates, chemicals and polymers. CO_2 usage is a form of 'circular economy' in its own right, taking emitted ("waste") CO_2 and using it to create other carbon-containing molecules, ideally instead of non-circular (and even hydrocarbon) alternatives. This has given rise to the terms, borrowed from elsewhere in cleantech, 'carbon-to-value' / 'circular carbon economy'.

Globally, already some 250 million tonnes (Mt) of CO_2 are used every year, in applications like fertiliser (urea), oil & gas (EOR) as well as food & beverages.

CO_2 use does not necessarily reduce emissions and quantifying the climate benefits is complex, requiring a comprehensive life-cycle assessment as well as an understanding of market dynamics. CO_2 use can provide climate benefits where the application is scalable, uses low-carbon energy, and displaces a product with higher life-cycle emissions.

Captured CO₂ Uses



Source: IEA (2019)

CO_2 usage as a feedstock can be classified as two types: 1) 'without conversion', where the CO_2 is used directly; and, 2) 'with conversion', where CO_2 is converted to chemicals and fuels via carboxylation or reduction avenues.

The IEA has identified five main usage classifications for captured CO_2, based on criteria such as their CO_2 consumption, economics and technical viability. These are:

– <u>CO_2-derived fuels</u>: The carbon in CO_2 can be used to produce fuels that are already in use (e.g. methane, methanol, gasoline, aviation fuels).

– <u>CO_2-derived chemicals</u>: The carbon (and oxygen) in CO_2 can be used as an alternative to fossil fuels in the production of chemicals (e.g. plastics, fibres and synthetic rubber).

– <u>Building materials from minerals and CO_2</u>: CO_2 can be used in the production of building materials, e.g. to replace water in concrete ('CO_2

curing'), or as a raw material in its constituents (cement and construction aggregates). These applications involve the reaction of CO_2 with calcium or magnesium to form low-energy carbonate molecules (the form of carbon that makes up concrete).

– Building materials from waste and CO_2: Construction aggregates (small particulates used in building materials) can be produced by reacting CO_2 with waste materials from power plants or industrial processes.
– Crop yield boosting with CO_2: CO_2 can be used to enhance yields of biological processes, such as algae production and crop cultivation in greenhouses.

Historically the high chemical stability of CO_2 – which is indeed why it resides for such a long period in the atmosphere – has led to the view that any chemical conversion of it will necessarily require high energy input, and therefore not be commercially viable. Now a number of emerging technologies – mostly involving catalytic reactions - are coming to market with viable approaches to utilising CO_2 as a chemical feedstock (and "fixing" it to molecules in the process).

A 2019 study in Nature identified 10 different pathways (see table below) for CO_2 usage (each with the potential to store at least 0.5GtCO_2 per annum), classified as:

– 'cycling': moving carbon through industrial systems over timescales of days, weeks or months;
– 'closed': utilisation and near-permanent CO_2 storage;
– 'open': i.e. "leaky", with the risk of large-scale flux back to the atmosphere, usually based in biological systems.

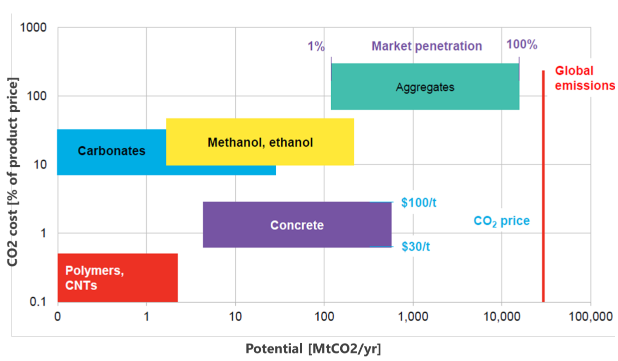
CO_2 Usage & Removal Pathways

Pathway	Description
Chemicals from CO_2	Catalytic chemical conversion of CO_2 from flue gas or other sources into chemical products
Fuels from CO_2	Catalytic hydrogenation processes to convert CO_2 from flue gas or other sources into fuels
Products from microalgae	Uptake of CO_2 from the atmosphere or other sources by microalgae biomass
Concrete building materials	Mineralization of CO_2 from flue gas or other sources into industrial waste materials, and CO_2 curing of concrete
CO_2-EOR	Injection of CO_2 from flue gas or other sources into oil reservoirs
BECCS	Growth of plant biomass
Enhanced weathering	Mineralization of atmospheric CO_2 via the application of pulverized silicate rock to cropland, grassland and forests
Forestry techniques	Growth of woody biomass via afforestation, reforestation or sustainable forest management
Soil carbon sequestration techniques	Increase in soil organic carbon content via various land management practices
Biochar	Growth of plant biomass for pyrolysis and application of char to soils

Source: Nature (2019)

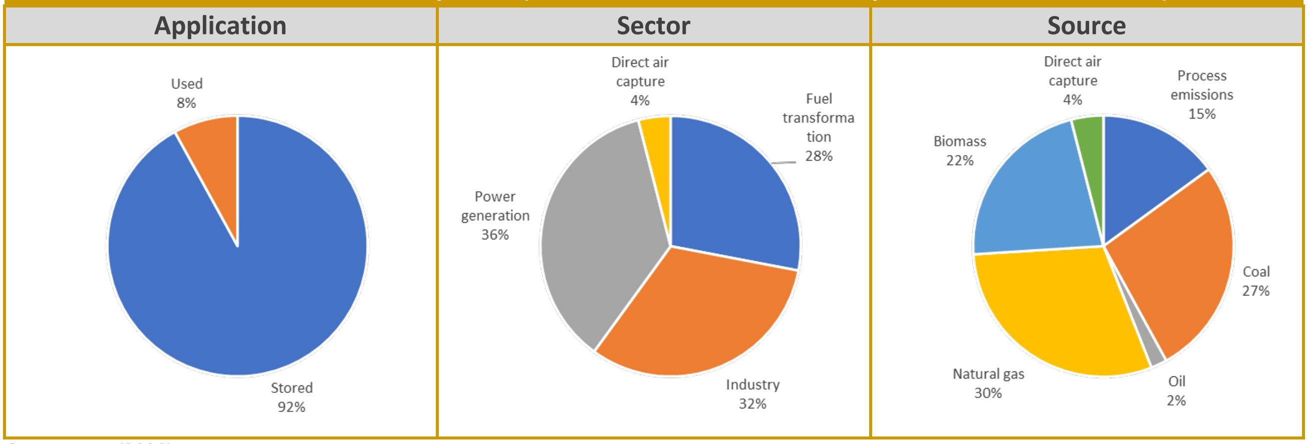
There are complex considerations for any existing industry to adopt CO_2 as a feedstock, at least without any government directives and targets (watch this space!). What is interesting though is that in some applications CO_2 can be a less expensive feedstock and can even provide higher functionality than the incumbent. In other cases, any CO_2 feedstock premium can be significantly diluted by the CO_2 being a tiny proportion of the overall cost, as is the case in concrete.

CO_2 Applications & Sensitivity to CO_2 Price



Source: Bloomberg NEF

Global Cumulative CO_2 Captured (under IEA Sustainable Development Scenario, 2020-70)



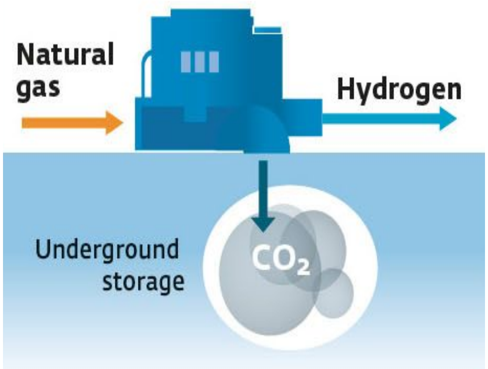
Source: IEA (2020)

CCUS & THE HYDROGEN ECONOMY

Recent years have witnessed greatly heightened interest in hydrogen as a key vector for the 'Energy Transition', with the Carbon Economy's sister term emerging, the 'Hydrogen Economy'. While in general the end-game is considered to be 'green' hydrogen (based 100% on zero emissions electricity), most – though not all – commentators expect a substantial role for 'blue' hydrogen over the medium-term.

'Blue' hydrogen refers to the production of hydrogen from natural gas (through either steam-methane reforming or through autothermal reforming) where the associated CO_2 emissions are captured through conventional point source approaches. The production of 'blue' hydrogen for de-carbonization offers several advantages in the near- to medium-term as it utilises the currently conventional, large-scale commercial hydrogen production pathways and infrastructure (~75% of global hydrogen production globally already relies on natural gas and only 1% is 'green' hydrogen) and is significantly lower cost (till at least 2030).

'Blue Hydrogen': CCUS & Hydrogen

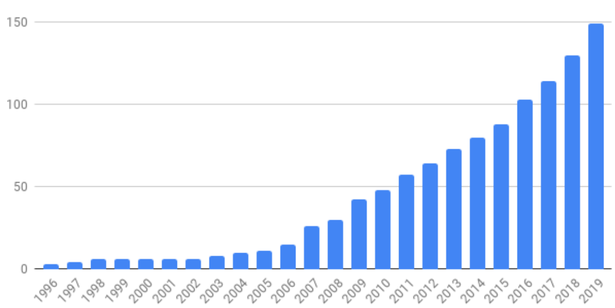


Source: The World of Hydrogen

CCUS COMPANIES IN EUROPE

Carbon Economy and ClimateTech innovation is occurring worldwide, at universities, within large corporates, and of course within the start-up community. The same holds specifically for the CCUS space. According to Circular Carbon, **at end-2019 there were 150 CCUS start-ups worldwide**.

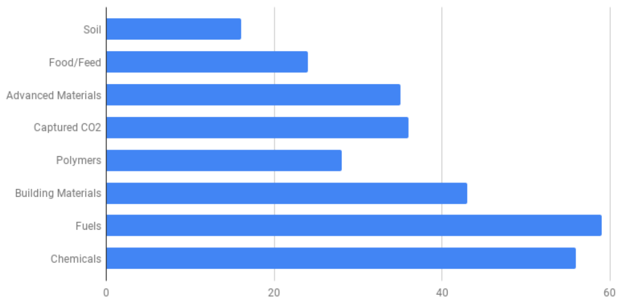
Cumulative # CCUS Start-ups Founded



Source: Circular Carbon

With regards to start-up activity in CCUS, most relates to CO_2 capture and usage, the other sections of the value chain (transport, storage) being more capitalintensive and the natural domain of large oil & gas, chemical, infrastructure and industrial players.

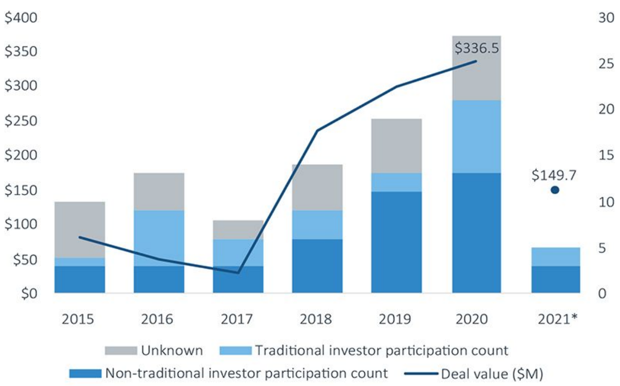
Start-ups Count by Focus



Source: Circular Carbon

According to data from PitchBook, **in 2020 ~$340 million was invested globally in CCUS start-ups, in a total of 28 deals**.

CCUS VC Investment [US$ m]



Source: PitchBook

Europe is a hotbed of activity in the CCUS sector, and not just because of the recent heightened interest in the space. Many of the pioneers of CCUS in Europe were founded in the early part of the last decade. Some of the leading European CCUS start-ups are highlighted below.

European CCUS Start-ups

Capture	Use
ClimeWorks [CH]	**Econic [UK]**
C-Capture [UK]	Sunfire [DE]
Carbon Clean [UK]	**Photanol [NL]**
MOF Technologies [UK]	Electrochaea [DE]
Hydrocell [FI]	Made of Air [DE]
Skytree [NL]	Carbofex [FI]
	LiquidWind [SE]
	Carbfix [IS]
	Deep Branch [UK]

Source: CleanTech Capital Advisors

Econic Technologies is a UK-based company deploying proprietary catalyst chemistry to turn CO_2 into polymers (initially polyols used in the production of polyurethane). The technology produces both economic benefits (CO_2 as a less expensive chemical feedstock) as well as environmental impact (reducing the reliance on fossil fuels and serving as a sink for "waste" CO_2). Econic's unique catalysts manage to bind CO_2 into polymer chains with relatively low energy, making its use as a feedstock vastly more viable. The company is currently actively commercialising its technology.

Amsterdam-based **Photanol** is a platform renewable chemical company that utilises proprietary engineered cyanobacteria to process CO_2 and sunlight into valuable chemical products (returning oxygen as a by-product). In 2020 the company completed construction of its first demonstration plant.

MOF Technologies is a pioneer in the development and commercialisation of metal organic frameworks (MOF), an emerging super-adsorbent material. MOFs enjoy many advantages over traditional adsorbents (zeolites, aluminas, silicates, activated carbons). In a CO_2 capture context, MOF-based systems can halve the energy requirements vs. amine-based solutions.

Climeworks is one of the leading CCUS start-ups globally, having raised CHF134 million in capital since inception. Climeworks built and operates the world's first commercial DAC plant (using mainly low-grade heat as energy source). The pure CO_2 gas is sold to customers in key markets, including: agriculture, food & beverage, energy and automotive. In 2019 Climeworks acquired Antecy, a Dutch DAC provider.

C-Capture has developed a low-cost, energy efficient and safe technology to capture CO_2 from the flue gas streams of power stations. The solvent-based technology has substantially better environmental characteristics vs. incumbent approaches. C-Capture currently leads a major collaborative project (funded by BEIS) to scale-up and deploy its technology at a major Drax power station.

Carbon Clean was founded in 2009 and offers CCUS solutions, including systems, solvents, licensing and engineering services. The company has fitted almost 40 facilities globally, claiming ~90% CO_2 capture rates. So far the company has raised £56 million in equity, including from high profile strategics such as Equinor, Chevron and Marubeni.

Liquid Wind develop, finance, build and manage facilities to convert CO_2 emissions and green hydrogen into valuable, carbon neutral fuel – 'eMethanol'. The derived fuel will support the transition to net zero shipping, road transport and in the chemical industry. In collaboration with a prestigious technical consortium, Liquid Wind are now developing their first commercial-scale eMethanol facility in Sweden.

CleanTech Capital Advisors considers the CCUS subsector to be a very attractive opportunity for financial and corporate investors, and is not yet overheating, unlike certain other cleantech subsectors. However, generally the underlying technologies are complex and adoption times are long. In addition, the climate change stakes are multi-decadal and not necessarily in sync with typical investor horizons. However, we anticipate that giants will emerge among this European CCUS cohort.

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CleanTech Capital Advisors is a pioneering corporate finance advisory firm, providing transaction advisory services for companies in the CleanTech sector. We achieve optimal transaction outcomes for our clients through perfection of their equity story, knowledge- and relationship-based matching to the relevant counterparties, as well as rigorous process management. Since 2012 we have advised many of the most disruptive European cleantech start-ups.

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