OIL AND GAS CLIMATE INITIATIVE

WHITE PAPER

Carbon capture and utilization as a decarbonization lever

APRIL 2024

About The Oil and Gas Climate Initiative

The Oil and Gas Climate Initiative is a CEO-led organization bringing together 12 of the world's largest oil and gas companies to lead the industry's response to climate change. It aims to accelerate action towards a net zero emissions future consistent with the Paris Agreement.

OGCI members are Aramco, bp, Chevron, CNPC, Eni, Equinor, ExxonMobil, Occidental, Petrobras, Repsol, Shell and TotalEnergies. Together, OGCI member companies represent almost a third of global oil and gas production.

OGCI members set up Climate Investment to create a US$1 billion-plus fund that invests in companies, technologies and projects that accelerate decarbonization in energy, industry, built environments and transportation.

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EXECUTIVE SUMMARY

Carbon capture and utilization as a decarbonization lever

The Oil and Gas Climate Initiative (OGCI) is working with industry, governments and other investors to scale up carbon capture, utilization and storage (CCUS), in particular through the development of CCUS hubs.

Carbon capture and utilization (CCU) specifically could be a lever for decarbonization because it captures carbon dioxide (CO_2) emissions from industries and reuses/recycles the carbon for a different purpose, thus enabling a more circular economy. Estimates of the size of the CO_2 utilization market in the future vary widely from between 10%-33% of total captured carbon.

Today, most utilized CO_2 is channelled into either enhanced oil recovery (EOR) or urea production, with a market size estimated at ~250 million tonnes per annum (Mtpa) of CO_2.

There are several utilization technologies across key pathways that may develop and increase the utilization of CO_2 to ~430-840 Mtpa by 2040. This compares with the need for CO_2 emission reductions in the gigatons per annum scale, suggesting that although utilization may have a part to play in decarbonization, it will likely be relatively small compared to CO_2 storage. However, each CCUS hub is unique and it is likely CCU may have a more significant role in some hubs.

This study only covers conversion pathways, not direct uses of CO_2 (such as EOR) and focuses on those with global impact potential. It looks at four promising CO_2 utilization pathways through to 2040, their CO_2 utilisation potential and key barriers:

- **Construction aggregates** make up the largest potential market by far in terms of CO_2 volume (estimated at ~0.5Gt CO_2 per year), but low product value makes it challenging to compete with low-cost conventional aggregates.

- **CO_2-cured concrete** is a small market in terms of overall CO_2 required (estimated at 40-70 Mtpa CO_2 per year), but the technology is nearly ready for scaling. The economics can be challenging, given high capex requirements for a low-value product.

- **E-fuels:**
  - **E-kerosene** is a medium-sized market (estimated at 50-150 Mtpa CO_2 per year) and technology is nearly ready for scaling. However, overall cost is expected to stay well above conventional and other bio-based kerosene prices without significant regulatory incentives; the scarcity of biogenic CO_2 and the cost of direct air capture (DAC) could be a limiting factor.
  - **E-methanol** is a medium-sized market (estimated at 130-280 Mtpa CO_2 per year) and technology is nearly ready for scaling. However, given that high energy requirements drive the bulk of production cost, the business case is likely to be negative without financial incentives or sufficient low-cost hydrogen (H_2); scarcity of biogenic CO_2 and the cost of DAC could also be a limiting factor.

There are some earlier stage CO_2 uses in the chemical sector to monitor (e.g., green methanol to olefins (MTO), dimethyl ether, and formic acid) and some developing uses (e.g., polymers) that could become small to medium-sized markets. Interesting markets that are gaining traction also include leveraging CO_2 to create proteins for animal feed and producing ethanol using CO_2-based microbes.

There are still common technical hurdles to many of the synthesis pathways: high energy use, expensive inputs (e.g. CO_2 feedstock, green H_2), and commercial grade catalysts – all of which will require time and investments to solve.

Four key factors to realize the market potential of many of these utilization pathways include the cost and availability of CO_2 capture, the source of CO_2 (i.e., biogenic versus fossil CO_2), the cost of transporting CO_2, and the availability of low-cost renewable energy.

Climate impact

A layer of complexity in the business model of CCU is developing either product carbon footprints (PCF) that measure the greenhouse gas (GHG) emissions impact of a specific product/service or lifecycle assessments (LCA) that measure the broader environmental impact beyond GHG.

PCF and LCA consider the direct impact either from cradle-to-gate or cradle-to-grave depending on the assessment required. They can provide customers and markets with the information to assign a premium against versus the alternative products' PCF and LCA evaluations.

While there are several methodologies available, this report uses a simplified approach to LCA looking at only the carbon impact through a side-by-side comparison of the key process steps that differ between the CO_2-derived process and conventional process.

Overall climate impact can be categorized into carbon removals (i.e., increasing a theoretical global CO_2 budget), reductions (i.e., slows down use of a theoretical CO_2 budget), or avoidance (i.e., neutral impact on a theoretical CO_2 budget). The impact varies considerably based on source of CO_2 and whether CO_2 is re-emitted at the end of product's life. This paper leverages academic studies and reports that use different approaches to lay out the range of expected CO_2 impact. There is considerable variance due to lack of consistent approaches used today and differences between regions and technologies.

Rules around carbon accounting in both the voluntary and regulatory schemes are still evolving. The way in which climate benefits can be realized from CO_2 utilization may change over time and vary by region. For example, in the EU, fossil CO_2 can be used for synfuels until 2040, after which only DAC or biogenic sources will be recognized. In the absence of clear rules, CO_2 derived products could run the risk of being perceived as greenwashing by end customers if they do not lead to CO_2 removal and reduction (i.e., are only a CO_2 avoidance).

The ranges of potential carbon impact for the four key CO_2-derived products are as follows:

- **CO_2-based construction aggregates** are estimated to reduce the CO_2 emitted from a ton of aggregate by 12 to 48 kg. Compared to the conventional product with an average emissions of 3 kg per ton, the CO_2-based aggregates have -9 to -45 kg emissions (i.e., negative emissions) per ton. Given that the carbon is sequestered permanently in the construction aggregate, there is typically a net climate benefit.
- **CO_2-cured concrete's** abatement potential is highly dependent on the raw material mix as well as energy volume and intensity for carbonation in the range of 0-413 kg CO_2 per ton (-100% to +5% vs. conventional product). However, given that the CO_2 that is utilized is mineralized into concrete permanently, utilization can be considered equivalent to storage in terms of permeance as long as the process emissions of utilization are not worse than that of the conventional product.
- **E-fuels: E-kerosene's** CO_2 abatement potential can be up to 98% (synfuels) in cradle-to-grave studies on sustainable aviation fuel (SAF). **E-methanol's** CO_2 abatement potential ranges between 30% to 87%-98%. High abatement depends on use of /access to abundant biogenic CO_2 (based on the right feedstock and type of generation) or cost-efficient DAC.

Building the business case

Many of the CO_2 utilized products are still relatively new or under development. The regulatory and policy environment of markets is critical to scaling. Regulation today tends to focus on capture and/or storage rather than utilization, where there is still a gap.

However, specific markets such as the US (where there are subsides for utilization technologies) and EU (where there are fuel mandates) are likely to enable further development and scaling of key utilization technologies. Other markets, where CCUS policies are still under development, such as China, India, as well as several Middle Eastern, African and South American countries, should be observed given increasing interest by key players and/or strong fundamentals (e.g., low-cost renewable energy).

The relative unit economics of each key CO_2-derived product today is considerably higher than the conventional product (between 1.5x-5x), and regulatory enablers such as mandates, ETS/carbon pricing, and incentives/subsides will play a big role in scaling:

- **CO_2-based construction aggregates** are currently two to four times more costly than incumbent and requires landfill tax of ~$50-$100 to incentivize using waste streams for construction aggregates instead of putting them in landfills.

- **CO_2-cured concrete** is currently one-and-a-half times to two times as costly than conventional concrete and requires capex to decrease by 50% as well as carbon pricing of $125-$175 to be profitable.
- **E-fuels (E-kerosene and E-methanol)** are currently two to four times more expensive than regular jet fuel and methanol depending on subsidy availability, the cost of hydrogen, and access to biogenic CO_2 or cost-efficient DAC. Existing or new fuel mandates, subsides, carbon pricing and market-based mechanisms could make E-SAF profitable before 2040, whereas e-methanol requires higher carbon prices of $200-$450 to break even.

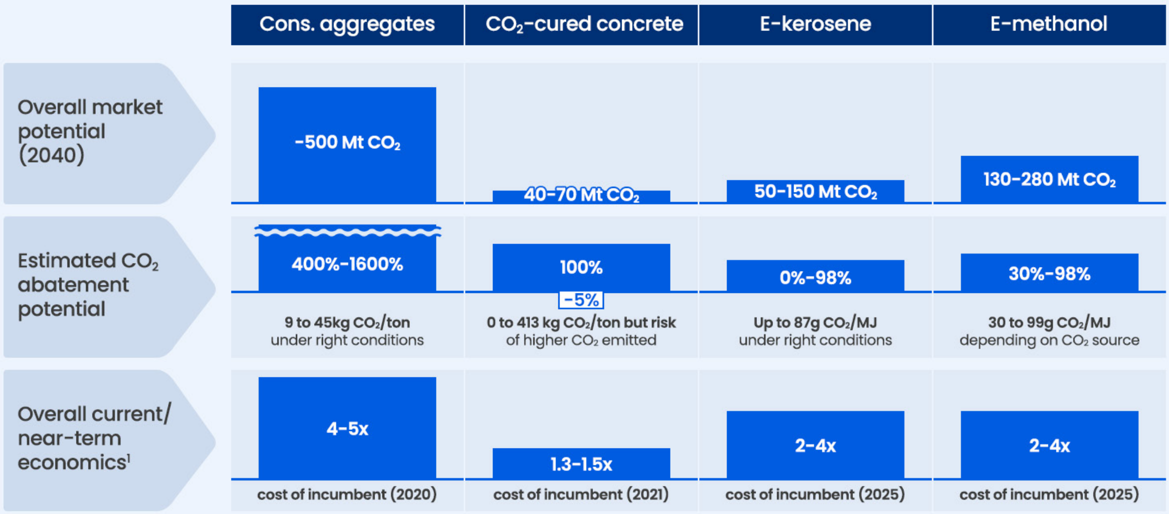
While the economics are not yet favorable, indirect policies such as carbon taxes and emissions trading systems can play a big role in making products economically viable. CO_2 utilization, specifically for synfuels, looks more promising than it did several years ago thanks to significant regulatory and technological developments.

The market for CCU is expected to remain relatively small in the short term, but there is scope for corporates, governments, and other key stakeholders to support research and development (R&D) for the development of technology and to start investing early to build the required markets.

CCU can be a decarbonization lever in the medium- to longer-term, but it is critical that the right set of inputs - the energy mix, green H_2, raw material mix, for example - and technology are leveraged in the processes used to create CO_2-derived products that support climate goals. However, it is important to note that even with the right set of inputs and technology, CCU is unlikely to have the scale to substitute for CO_2 sequestration. This will moderate its part in meeting global decarbonization goals.

EXHIBIT 1

Overview of market potential, CO_2 abatement potential, and estimated economics of four key CCU products



1. Range considers both with and without existing incentives;
Source: Sick. et al CO_2 Utilization and Market Size Projection, GCCA, IEA, Expert Interviews, BCG analysis

INTRODUCTION

Carbon capture and utilization as a decarbonization lever

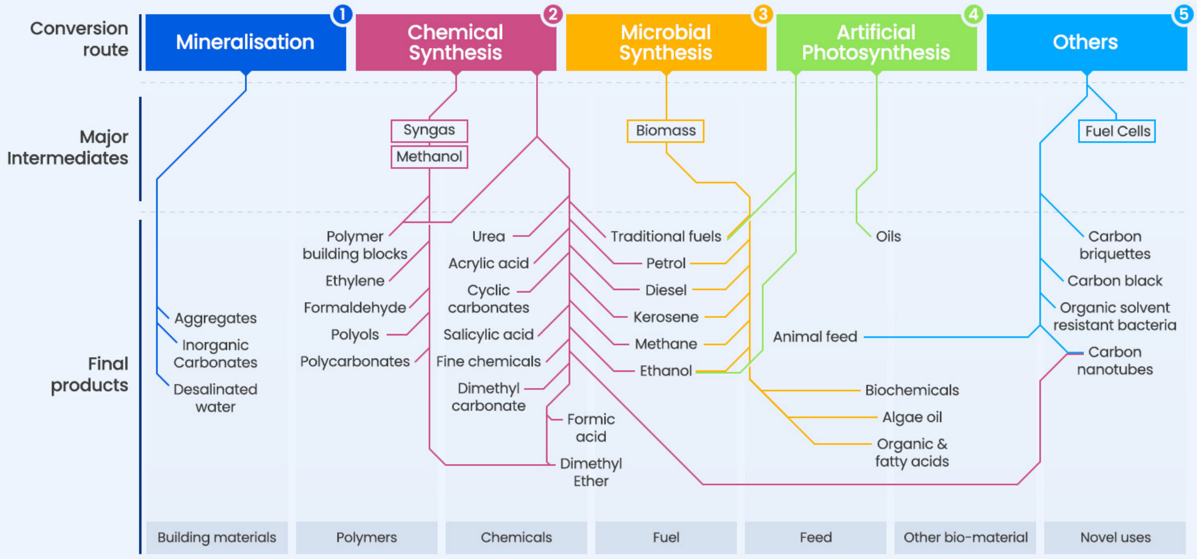
This paper explores the role that CO_2 utilization can play in decarbonization, the key utilization pathways involved, and their overall market potential. This study only covers conversion pathways, not direct uses of CO_2 (e.g., enhanced oil recovery).

Carbon capture, utilization and storage (CCUS) will need to increase by ~90 times from 2022 to reach ~4.0Gt by 2040 and 6.0Gt by 2050, based on the September 2023 update from the International Energy Agency (IEA) Net Zero Emissions by 2050 Scenario (NZE), which is a 1.5-degree scenario. Although captured carbon can either be utilized or stored, much of the industry and regulatory focus to date has been on storage.

The key markets for carbon utilization today are primarily in urea and enhanced oil recovery (EOR), with total demand estimated at ~250 Mtpa CO_2. This is expected to evolve over time with several alternative pathways under development that may significantly increase the amount of CO_2 utilized (Exhibit 2). This volume could increase to anywhere between ~430 to 840 Mt CO_2 by 2040. The wide range is due to the diverging estimates of the total utilization market, which could be 10-33% of total CO_2 captured by 2050.

EXHIBIT 2

Conversion routes offer a wide range of final products utilizing captured CO_2



Source: BCG analysis

Carbon capture and utilization (CCU) is perceived as a lever in decarbonization because it captures CO_2 emissions from industries and reuses/recycles the carbon for a different purpose, thus enabling a more circular economy. CCU is generic terminology that can be used for many types of technologies which start from CO_2 and generate a product or value (i.e., enhanced carbonated products, chemical feedstock, synthetic fuels, etc.).

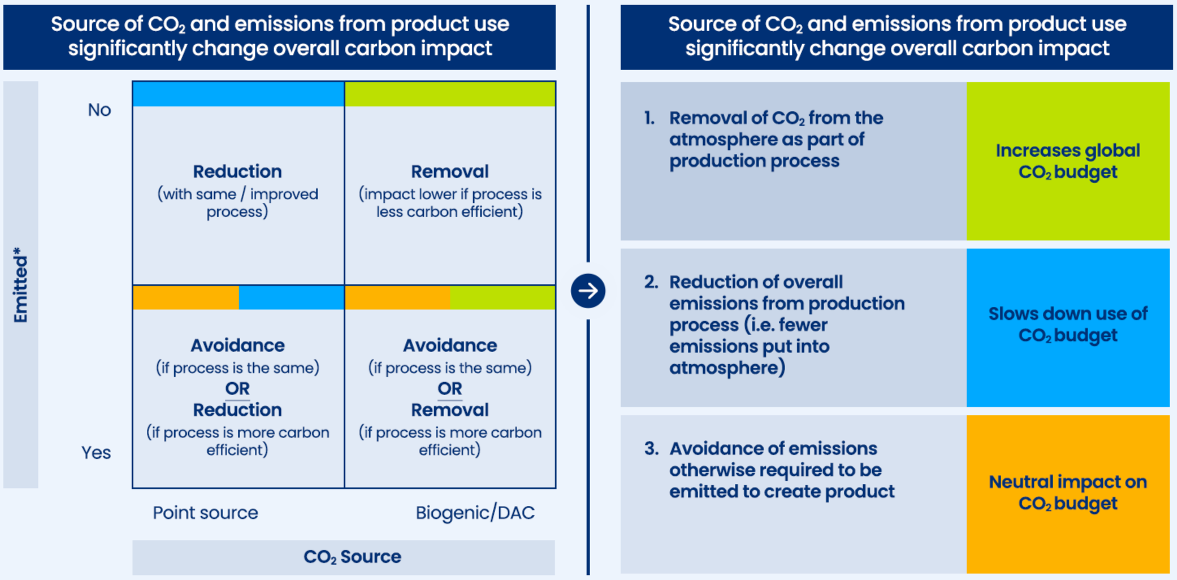
CCU could therefore contribute to a low-carbon future by reducing emissions (either because the CO_2 is sequestered into a product or because of process efficiencies), creating new economic opportunities, and reducing emissions from hard-to-abate sectors. It also does not require storage sites that are not always easily available today and are not distributed evenly worldwide.

However, it is critical to ensure that utilization pathways benefit from the right set of inputs, technology, and processes to enable a positive carbon impact. Product carbon footprint or life cycle analysis from "cradle-to-grave" enables an assessment of the carbon impact. The carbon/environmental impact of each pathway needs to be considered individually, given the unique nature of the technologies as well as the product properties.

The carbon impact and decarbonization potential of each CO_2-derived product is highly dependent on the source of CO_2 utilized, the efficiency of production process to make the CO_2-derived product compared to a conventional product, and whether CO_2 is emitted during use (Exhibit 3).

EXHIBIT 3

Overall impact of CO_2 derived products is dependent on source of CO_2, efficiency of production process, and whether CO_2 is emitted during use



Source of CO_2 and emissions from product use significantly change overall carbon impact

Emitted*	Point source	Biogenic/DAC
No	🟦 **Reduction** (with same / improved process)	🟩 **Removal** (impact lower if process is less carbon efficient)
Yes	🟧🟦 **Avoidance** (if process is the same) **OR** **Reduction** (if process is more carbon efficient)	🟧🟩 **Avoidance** (if process is the same) **OR** **Removal** (if process is more carbon efficient)

CO_2 Source

Source of CO_2 and emissions from product use significantly change overall carbon impact

1. Removal of CO_2 from the atmosphere as part of production process	🟩 **Increases global CO_2 budget**
2. Reduction of overall emissions from production process (i.e. fewer emissions put into atmosphere)	🟦 **Slows down use of CO_2 budget**
3. Avoidance of emissions otherwise required to be emitted to create product	🟧 **Neutral impact on CO_2 budget**

*If CO_2 is not re-emitted and overall LCA is not worse than counter- factual, then CCU route is equivalent to CCS

The potential benefits of CCU pathways with a positive impact must be balanced against risks such as:

- Regulatory guidelines on emissions accounting: legislation around emissions accounting may differ amongst regions and across product ranges and is subject to change.
- Energy requirements: there is potential risk associated with investing in development of energy-intensive pathways/products without decarbonization of the electricity grid or fuel.
- End-customer perception: despite following relevant legislation and utilizing renewable energy, CO_2-derived products could still run the risk of being considered ‘greenwashing’ if they do not actually reduce or remove emissions.

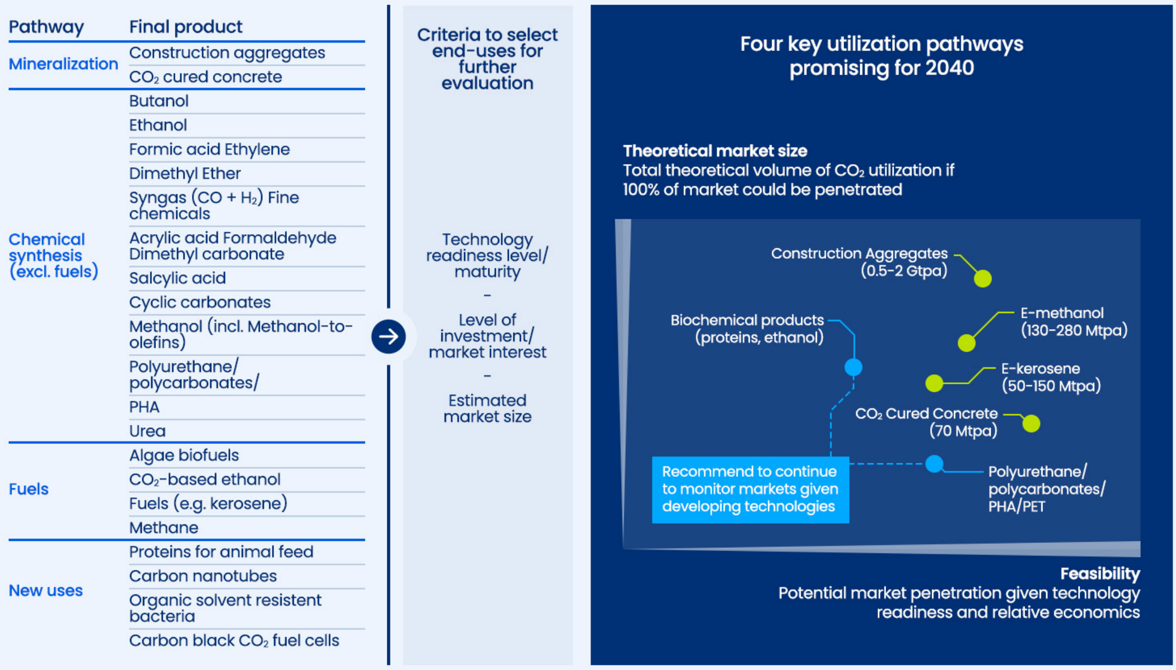
CHAPTER ONE

The fast-evolving market landscape

There are more than 25 different utilization pathways that could materialize over the next decade or two to create building materials, chemicals, fuels, proteins, etc. Based on technological readiness and overall maturity, level of market interest (i.e., investment) and estimated market size, this study provides a perspective on four key utilization pathways that look promising for 2040 in terms of both market potential and feasibility, as per Exhibit 4.

EXHIBIT 4

List of potential utilization pathways at varying levels of maturity



Pathway	Final product
Mineralization	Construction aggregates
	CO_2 cured concrete
Chemical synthesis (excl. fuels)	Butanol
	Ethanol
	Formic acid Ethylene
	Dimethyl Ether
	Syngas ($CO + H_2$) Fine chemicals
	Acrylic acid Formaldehyde Dimethyl carbonate
	Salcylic acid
	Cyclic carbonates
	Methanol (incl. Methanol-to-olefins)
	Polyurethane/ polycarbonates/
	PHA
	Urea
Fuels	Algae biofuels
	CO_2-based ethanol
	Fuels (e.g. kerosene)
	Methane
New uses	Proteins for animal feed
	Carbon nanotubes
	Organic solvent resistent bacteria
	Carbon black CO_2 fuel cells

Criteria to select end-uses for further evaluation

Technology readiness level/ maturity

-

Level of investment/ market interest

-

Estimated market size

Four key utilization pathways promising for 2040

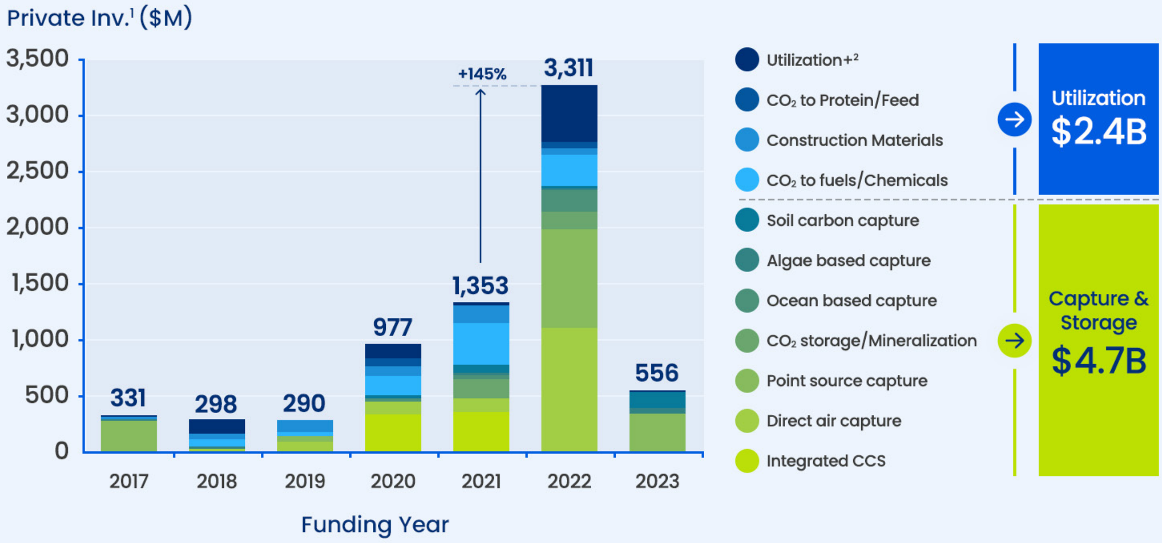
- **Construction aggregates** show the largest potential market by far in terms of CO_2 volume (estimated at 0.5-2Gt), but low product value makes it challenging for them to compete with the very low cost of conventional aggregates.
- **CO_2-cured concrete** is a small market in terms of overall CO_2 required (estimated at 40-70 Mtpa), but technology is almost ready for scaling, and is economically viable for specific use cases.
- **E-kerosene** is a medium-sized market (estimated at 50-150 Mtpa) and technology is nearly ready for scaling. However, the overall cost is expected to stay well above conventional and other bio-based kerosene prices without significant regulatory incentives; scarcity of biogenic CO_2 could also be a limiting factor.
- **E-methanol** is a medium-sized market (estimated at 130-280 Mtpa for both fuels and chemicals) and technology is almost ready for scaling; but the business case is likely to be negative without financial incentives or sufficient low-cost H_2, due to high energy costs of production; scarcity of biogenic CO_2 could also be a limiting factor.

There are several CO_2 utilization pathways where the technology is still developing, but should be monitored going forward given potentially sizable markets. These include green methanol to olefins, dimethyl ether, formic acid, polymers, and CO_2-derived proteins, and CO_2 to ethanol.

As shown in Exhibit 5, private investment in CCUS overall has increased considerably since 2017 and by 145% between 2021 and 2022, largely driven by DAC and Integrated Carbon Capture and Storage (Integrated CCS). Utilization has received around half the investment amount put into capture and storage, with most market interest being in CO_2 to fuels and chemicals, demonstrating that investors recognize the potential of these key pathways.

EXHIBIT 5

-$7.1B invested in CCUS since 2017 with strong YOY growth driven by DAC and integrated CCS in 2022; capture & storage received -2x utilization investments



[1] 23% investments undisclosed; private investments refer to investments by VC/PE, corporate venture, financial institutions. Analysis focused on CCUS companies receiving private investments since 2017.

[2] Includes companies that go beyond CO_2 utilization or have diversified end products from CO_2 utilization. Source: Quid; GIA; PitchBook, BCG Analysis.

CHAPTER TWO

Attractive utilization pathways for 2040

The following is a summary of the four most attractive and feasible utilization pathways, including an overview of the production process, the potential carbon impact, estimated market potential, and the unit economics.

Construction aggregates

Overview of production process (and key differences in CO_2-derived process)
CO_2-derived construction aggregates are primarily produced through the carbonation of waste by-products (iron slag, coal fly ash, etc.). Captured CO_2 is transported to a carbonation plant, where the granules of waste are enriched with CO_2. Aggregates are then typically transported to concrete plants.

Compared to a conventional construction aggregate process, the CO_2-derived process requires a viable waste stream (e.g., solid ash known as Air Pollution Control Residues), thereby adding a step in the process, but reduces the need for mining (including crushing/grinding). The CO_2 used for the carbonation process is mineralized in the construction aggregates and is not reemitted. Depending on the transport distances, the raw material mix (e.g., using pre-existing waste streams), and the energy mix (high energy requirements for carbonation process), CO_2-based production could lead to a carbon saving of 12-48 kg CO_2 per ton of aggregate, which represents an abatement potential of 400%-1,600% compared to the conventional product.

Another more nascent production process of CO_2-derived construction involves carbonation of granules, where recycled concrete is crushed into granules rather than using a more typical waste stream such as iron slag or coal fly ash. There are also other substrates that are utilized for carbonation (e.g., serpentine, olivine, etc.) which have not been considered for this study. However, there are various companies actively developing technologies using these substrates that should be monitored.

Range of market potential (e.g., tons of CO_2 pa by 2040)
The CO_2 utilization potential of construction aggregates in 2040 could be considerable at ~0.5 Gtpa CO_2, but this is contingent on the secondary process of carbonating granules being utilized. This is because waste stream availability could limit CO_2 utilization to ~250-300 Mtpa for conversion via the primary process of waste carbonation. It also assumes a penetration rate of ~2% of the construction aggregates market and ~0.26 tons of CO_2 utilized per ton of construction aggregate. Some reports estimate CO_2 utilization potential of up to 2Gt, but this would require ~25% penetration of CO_2-derived construction aggregates in markets such as the EU and US, where in reality, the availability of waste would be a limiting factor.

CO_2-derived construction aggregates are technologically ready, with Carbon8 claiming that their technology is scalable and trials having been successfully completed. Carbon8 is starting to expand internationally and is working with partners such as CPP Building Products, but their business case requires a waste treatment fee. Other players, such as Neustark, Orbix, and Blue Planet Systems, have patented mineralization technologies, and also display potential to scale.

View of economics for construction aggregates at Energy from Waste (EfW) and cement plants
The economic viability of CO_2-derived construction aggregates is especially challenging due to the low cost of conventional construction aggregates: CO_2-derived construction aggregates are between four to five times more expensive without landfill tax rates. Landfill tax rates are important because they make can make it more expensive to discard waste streams than to utilize them. Therefore, regulatory incentives (including landfill tax rates), public procurement targets, and carbon pricing will be required to drive wide-scale adoption.

One of the key issues with the economics of CO_2-derived construction aggregates is the distance between cement plants where CO_2 can be captured and concrete plants, and the fact that waste streams may also need to be transported. Availability of low-cost CO_2 as well as co-location of new production sites and use sites will be critical for the economic feasibility of CO_2-derived construction aggregates. For existing production sites, the ones that are most cost competitive will likely be those that are closest to use sites.

Case studies

1 Carbon8

- **Overview:** Based in the UK and is the first company to use Accelerated Carbonation Technology (ACT) to treat industrial wastes to produce low-carbon products (aggregates, fertilizers).
- **Business model:** Sells a plug and play solution in the form of a CO_2ntainer with a modular capacity of 12,000-40,000 tons.
- **Technology:** CO_2ntainer captures CO_2 at the source, which becomes an ingredient to carbonate industrial residues destined for landfill; applications include cement blocks, road filler, and green roofing substrate. Treats residues including APCr (Air Pollution Control residues), fly ash, incinerator bottom ash, cement kiln dusts, and slags from iron and steel.

2 AggregaCO₂

- **Overview:** Based in Spain, the project will be built incorporating accelerated carbonation technology for the manufacture of aggregates (gravel) from the CO_2 captured from Repsol's Petronor refinery, and from waste, utilizing ashes from the gas purification systems of municipal solid waste incineration plants. The project is expected to go live in 2024.
- **Business model:** Transforms a waste product, the destination for which was its treatment and shipment to landfill, into a construction product using CO_2 , thereby promoting the circular economy and reducing the concentration of CO_2.
- **Technology:** OCO Technology Limited, a company specializing in carbon capture, sustainable construction products and waste treatment, will capture CO_2 in the industrial processes associated with oil refining to produce a CO_2-based aggregate that can be used as a raw material in the construction industry. It aims to capture and reuse 2,200 tons of CO2 per year for 56,000 tons/year of eco-aggregates produced.

CO_2-cured concrete

Overview of pathway and key process differences in CO_2-derived process

CO_2-cured concrete is an alternative to conventional concrete, capturing CO_2 as part of the carbonation process during mixing. CO_2-cured concrete requires less cement than the conventional process since this type of curing leads to higher strength. However, this concrete can usually only be used in the non-structural precast market. If CO_2-cured concrete were to be used for structural concrete, some studies suggest that it could pose a greater risk of steel corrosion due to the added CO_2.

Depending on the transport distances, raw material mix (e.g., amount of cement), technology (electricity consumption and CO_2 utilization rate) and energy mix (emission intensity of required energy for carbonation), CO_2-cured concrete emits 0-413 kg CO_2 per ton as compared to 240-420 kg CO_2 per ton of conventional concrete. **However, some studies show that if CO_2-cured concrete is not produced under the 'right' conditions (i.e., volume of cement in raw material mix, electricity consumption, energy mix), it could even be marginally worse from a carbon standpoint compared to conventional concrete** (as demonstrated in the University of Michigan Global CO_2 Initiative Study in 2021 with no changes to raw material mix versus conventional product).

Range of market potential (e.g., tons of CO_2 pa by 2040)

Even at an ambitious market penetration estimate of 30-50% CO_2 cured concrete in use by 2040, CO_2 utilization potential is only ~40-70 Mtpa. This is due to the low CO_2 utilization rate per ton of concrete (between 0.001-0.05 tCO_2 as per the University of Michigan Global CO_2 Initiative) and its likely applicability to only the non-structural precast concrete market segment.

Despite the smaller market potential, there are several players already deploying this technology. Solidia focuses on CO_2-cured concrete in the pre-cast concrete market and has raised over US$105 million in funding for its curing technology which leverages a specialized absorption chamber. Their cement is produced at a lower temperature than traditional Portland cement, resulting in a second area of advantage in the carbon intensity.

Their technology has been demonstrated in more than 50 concrete manufacturing facilities across 10 countries, including the US, Canada, and the UK. Other players include CarbiCrete and Denka who are also focused on the pre-cast segment, and Carbon Cure, which licences CO_2 mixing technology to both pre-cast and ready-mix manufacturers.

However, small concrete production plants – some as small as 25 tons per year - tend to be quite dispersed limit the ease of scaling the technology (i.e. investments for CO_2-curing chambers need to be made across multiple plants). Co-location of CO_2 source and site of use will likely be required due to high volume/low value nature of concrete as a product.

View of economics for CO_2-cured concrete
Compared to conventional concrete, CO_2-cured concrete is estimated to be 1.3 to 1.5 times more expensive. It is therefore only currently viable in specific use cases, for example where the CO_2 source is within about 160 km of the concrete plant). It is estimated that for CO_2-cured concrete to be 10-20% more expensive than conventional concrete, capex (driven by the equipment and carbonation chamber costs) must decrease by 50% and a carbon price of $125-$175 needs to be in place. Alternatively, public procurement targets or mandates could also increase the willingness to pay.

As with CO_2-derived construction aggregates, one of the key economic challenges of CO_2-cured concrete is proximity to a CO_2 source, given that concrete manufacturing plants tend to be dispersed. Therefore, the uptake of CO_2-cured concrete also depends on the availability of reliable and low-cost CO_2.

Case studies

1 Solidia

- **Overview:** Based in the US, a cement and concrete technology company that uses CO_2 to create sustainable building materials (concrete and cement).
- **Business model:** Solidia has curing chambers at 50+ facilities with industrial pilots and reports lower production costs, shorter curing times (<24h) and improved product performance.
- **Technology:** Sustainable concrete curing technology leveraging CO_2 for curing instead of water, permanently and safely consuming 240 kg of CO_2 every year and potentially saving 3 trillion litres of fresh water every year

2 Carbon Upcycling

- **Overview:** Canadian company harnessing the power of carbon dioxide to make materials more sustainable by enabling local, abundant and low-emissions production of some of the most common materials on the planet, such as cement, plastics, consumer products, fertilizers, and pharmaceuticals.
- **Business Model:** Focused on both concrete and advanced materials (e.g. plastics, paper, etc.,) working with global channel partners to deliver greener products.
- **Technology:** Novel technology platform unlocks new advances in strength and durability for cement replacements. Patented catalytic reactor works with a range of feedstocks where they are combined with a CO_2 source to create unique building materials that sequester CO_2.

E-Fuels (E-Kerosene and E-Methanol)

Overview of pathway and key differences in CO_2-derived processes
There are two ways to produce either e-kerosene or e-methanol. The first is common to both by combining H_2 and CO_2 through reverse water gas shift (RWGS) to create syngas that is then converted through the Fischer Tropsch (FT) process. Alternatively, e-kerosene can be produced via direct methanol synthesis, which is still a more nascent pathway. E-methanol can be produced by combining H_2 and CO_2 directly through co-electrolysis of CO_2 and water (or other direct catalytic hydrogenation). Both these direct and newer methods eliminate RWGS and are more efficient.

Producing e-kerosene or e-methanol that is to be marketed as carbon neutral would require the use of low carbon or renewable power, green H_2 and feedstock CO_2 derived from DAC or biogenic sources. Conventional kerosene and methanol both require natural gas and associated CO_2 which has to be transported and stored. If the source of the CO_2 is biogenic or from DAC and the grid power used for the production/synthesis process is renewable, e-fuels can often yield positive CO_2 abatement potential through reduced process emissions — even if the CO_2 is re-emitted when the fuel is consumed.

E-kerosene is typically used for aviation and the CO_2 is re-emitted. However, e-methanol can either be used directly as a fuel, in shipping for example, where the CO_2 is re-emitted, or it can be converted into olefins and aromatics, where the CO_2 is potentially stored for a longer period of time. This can be months or years depending on the product.

The CO_2 abatement potential of e-kerosene varies from 0-98% in cradle-to-grave studies on SAF (bio- and synfuels) for aviation, where conventional jet fuel has 89g CO_2/MJ whereas power-to-liquids (PtL) can be as low as 2g CO_2/MJ. For e-methanol, CO_2 abatement potential varies from 30% to nearly 98% in cradle-to-grave studies on synfuels.

This, of course, depends on the type of CO_2 used as input (e.g., biogenic CO_2 or DAC versus fossil CO_2), technology efficiency gains from advancement in transformation/synthesis, energy mix (emission intensity and availability of renewable energy) and the regulatory acceptance of market-based mechanisms for environmental attributes to assigned to specific products. High abatement depends on the use of and access to abundant biogenic CO_2, based on the right feedstock and type of generation, or cost-efficient DAC as well as low-cost renewable energy.

Range of market potential (e.g. tons of CO_2 p.a. by 2040)
Assuming that e-kerosene will make up approximately 3%-10% of the overall jet fuel market in 2040, the market potential for CO_2 utilization for this pathway is in the range of 50-150 Mtpa CO_2. The technology is close to ready for scaling with the FT route at Technology Readiness Level (TRL) 8-9 whilst RWGS is at TRL 6-7 with several pilots coming online in Europe between 2024-2026.

Depending on e-methanol adoption compared to other shipping fuels and grey methanol), it could make up between 10%-60% of the overall methanol market in 2040 (estimated at ~500 Mtpa by IRENA) for both fuels and chemicals. This results in a market potential for CO_2 utilization for this pathway is in the range of 130-280 Mtpa CO_2. This is mostly because the technology is close to ready for scaling in shipping; e-methanol for shipping could make up as much as 40% of the methanol market in 2040.

The likely higher penetration of e-methanol as compared to e-kerosene is due to technology (e.g., easier to synthesize from H_2 and CO_2 compared to kerosene), regulation (e.g., the aviation sector has lower pressure to decarbonize as quickly as compared to heavy industry), and the economics of alternatives (e.g., e-methanol is closer in cost to bio-methanol as compared to e-kerosene versus bio-based SAF).

However, both e-kerosene and e-methanol could be limited by the fact that there are several alternative options. Firstly for e-kerosene, biofuels are expected to dominate the sustainable aviation fuels market in the short term versus e-kerosene. Secondly, even though e-kerosene is a drop-in fuel with few infrastructure requirements, a potential limitation due to existing shared infrastructure exists if market-based mechanisms such as book-and-claim are not accepted under GHG inventory accounting practices and science-based net zero pathways.

Similarly, e-methanol's potential is limited by the fact that it competes with ammonia as an alternative low-carbon fuel in the shipping sector, and requires building low-carbon H_2 and associated logistics and CO_2 access, as well as bunkering for shipping. In the chemicals sector, the lack of a holistic value chain building policy approach limits the ability to scale production and infrastructure.

The high abatement potential of both e-kerosene and e-methanol depends on the use of and/or access to abundant biogenic CO_2, based on the right feedstock and type of generation), which is currently limited, or the emergence of cost-efficient DAC. This will become more relevant as the EU mandate is unlikely to accept use of fossil-based CO_2 by 2040. Separately, it is critical to set accounting rules for both e-methanol as a fuel - certification available under IMO regulations, for example - and as a sequestration method into plastics.

Despite potential limitations, there are several major e-kerosene projects expected online in the 2020s, largely in Europe where the EU fuel mandate is pushing development. Significant projects include the Norsk e-fuel project, the SkyNRG Stuttgart project, and the Shell e-fuel German project. There are three main types of players in the ecosystem including oil and gas companies, aviation offtakers, and tech developers such as SkyNRG and Neste.

Similarly, there are many e-methanol projects coming online in the late 2020s, especially in Europe and China. A couple small projects are already operational, including the George Olah renewable methanol plant in Iceland and the CO_2 hydrogenation-to-methanol technological development project in China.

Overview of economics for e-kerosene and e-methanol

The economics of both e-kerosene and e-methanol are very sensitive to cost of power, feedstocks, capex of the electrolyzer, and the capex of the FT process (or the other processes used to create e-kerosene).

The most feasible scenario for producing e-fuels today is in the US, where the Inflation Reduction Act (IRA) subsidy reduces the cost of producing green H_2. In the case of e-kerosene, exporting to Europe makes the most economical sense given that the EU fuel mandate requires 5% SAF to be used in air transport by 2030.

The landed cost of e-kerosene is estimated at \$6 to \$7 per gallon, which is two to four times more expensive than regular jet fuel. This cost range for e-kerosene assumes the power to leverage the IRA subsidy in the US as well as a \$6/kg cost of H_2. Even with the IRA tax credit and the EU fuel mandate in place, a carbon price of \$180 per t CO_2 (up to \$600 per t CO_2) is required for e-kerosene to break even in 2025.

The cost of e-methanol is estimated at \$900 to \$1200 per ton, which is two to four times more expensive than grey methanol. This cost range for e-methanol assumes being able to leverage the US' IRA subsidy as well as a \$6/kg cost of H_2. The high cost is driven by the cost of power and H_2, the cost of CO_2, as well as the capex associated with methanol synthesis, which can be up to \$4000/kW MeOH. Even with the IRA Production Tax Credit, a carbon price of at least \$330 per t CO_2 is required for e-methanol to break even in 2025.

Case studies

1 E-kerosene: Reuze Project

- **Overview:** The Reuze Project is based in France and is a e-kerosene, e-diesel and gasoline plant for maritime and aviation vehicles, to come online in 2026. They key players involved in the partnership include Infinium, ArcelorMittal, and Engie.
- **Business model:** Aims to convert 300k tons of CO_2 per year into 100k tons of e-fuels and clean burning naphtha to meet local demand for SAF, low carbon fuels for shipping, and other chemical/plastic applications.
- **Technology:** CO_2 will be captured by ArcelorMittal from its steel production facilities and then combined with green hydrogen, produced by a 400 MW electrolyzer, installed by Engie. Infinium will then use its patented technology for the production of e-fuels.

2 E-methanol: Carbon Recycling International

- **Overview:** Based in Iceland, CRI offers a world-leading process technology to produce methanol from carbon dioxide and hydrogen.
- **Business model:** Designs, licenses and sells proprietary Emissions-to-Liquids (ETL) process technology for producing green methanol from captured carbon dioxide emissions and green hydrogen. Aims to be the partner of choice for organizations seeking to commercialize potential projects by providing proprietary technology, licensing, engineering services, marketing and end logistics.
- **Technology:** RI's patented Emissions-to-Liquids ™ technology transforms carbon dioxide emissions and hydrogen into methanol for a greener, more renewable source of energy and chemical feedstock. First company to produce renewable methanol at an industrial scale; 2022 saw the commissioning of the world's first 110,000 tons/year capacity recycled carbon methanol production plant.

Key challenges and barriers to scaling for key utilization pathways

Overall, the market penetration and feasibility of these four utilization pathways is dependent on substantial regulatory incentives, carbon pricing, and/or public procurement targets to make the business case attractive. While technology readiness is relatively high for these pathways, there are a few common challenges including:

- CO_2 derived products are one-and-a-half to five times more expensive than the conventional product, which in the case of building materials are low value products.
- Significant carbon prices are required to make the derived products cost competitive – anywhere in the range of $125-$600 per t of CO_2.
- For building materials specifically, the small scale and localized production of aggregates and concrete limit the ease of scaling the technology, and co-location of CO_2 source and site of use is particularly critical.
- For e-fuels, the availability of low-cost renewables and thus, low-cost H_2 as well as availability biogenic CO_2 and/or cost-efficient DAC (in the longer term) is needed.
- Uncertainty over greenhouse gas emission accounting guidance for utilization pathways introduces additional risks into already challenging business plans.

Developing CCU pathways to monitor

Two other pathways of interest include polymers and biochemical pathway products (e.g., CO_2-based protein and ethanol). These are at earlier stages of technological development compared to the four pathways already discussed but are showing potential to be quite substantial by 2040.

Polymers
Producing polymers using captured CO_2 has the potential to develop into several small to medium-sized markets. There are five key end products of polymers: polycarbonates, polyols/polyurethanes, polyolefins, polyhydroxyalkanoates (PHA) and PET. Each has differing market size and penetration. Most notably, the technology required for each product is quite different and many are nascent today.

For example, polyolefins are the highest potential market with a theoretical market size of 60-120 Mtpa CO_2 (assuming 100% of green olefins produced via green MTO process are polyolefins and green penetration of 3%). However, the expectation for penetration is relatively low due to alternative bio-options. Polyols/polyurethanes display the highest maturity, but have a smaller market size of 10-15 Mtpa CO_2 (assuming 100% penetration of polyurethane market and high uptake scenario of 25% of CO_2 per ton of polyurethane).

There are three key challenges in the development of CO_2-derived polymers:

1. Regulatory incentives are currently prioritizing recyclability and biodegradability attributes rather than CO_2 content (e.g., EU legislation on packaging and packaging waste).
2. Technology around several polymer product pathways is still early stage and there are several low-carbon and bio competitors (e.g. bio-based polymers for PEF, electric steam cracking furnace for low carbon MTO).
3. The significant renewable energy needed to produce CO_2-based polymers could be a limiting factor (IEA estimates 11.7-petawatt hour of electricity required by 2030 to fulfil global primary chemical demand, ~10% of total energy supply in NZE 2030).

However, given that CO_2 utilization for polymers has some potential to be sizable, it is recommended to continue observing the technological and regulatory developments of this pathway and for greater government-led research and development in this area.

Selected biochemical products – focus on CO_2-based proteins and ethanol
CO_2-derived products through the biochemical pathway typically involve the use of microorganisms, such as bacteria, archaea, or algae , to convert CO_2 into valuable products — for example fuels, proteins, and ethanol.

Biofuels through algal synthesis are uneconomical despite many years of research and development, given their high energy demand and land requirements, but CO_2-based proteins and ethanol contain more potential to penetrate large existing markets.

Fermentation: CO_2-based proteins
CO_2-based protein production by microbes is a promising new CO_2 utilization pathway. There is a large market for animal feed, expected to grow over time, and within this, there is steady growth of the animal protein market of 3-4% per annum till 2040, with protein penetration potential of up to 10% by 2040. CO_2-based proteins through fermentation solve two environmental challenges: reducing the carbon intensity of the production process, and reducing the land used to grow animal feed.

Currently, there are more than 10 companies who are already looking to develop CO_2-based proteins. Two key players include Novo Nutrients, founded in 2017 which focuses on protein for food and feed, and Deep Branch, founded in 2018 and focusing on protein for animal feed. Deep Branch has a pilot-scale plant operational since April 2023 and a demonstration facility planned for 2026-2028. Deep Branch's process claims to provide animal feed producers a protein ingredient with up to 60% less CO_2 than conventional ingredients such as soy and fishmeal, and helps prevent deforestation. Methane-based protein production is the key competitive technology, but does not yield as much of a positive carbon impact.

Microbial synthesis: Ethanol
LanzaTech is the first public carbon capture company in the US to have scaled its proprietary microbial fermentation technology that uses CO/CO_2 as a feedstock. Their patented technology takes pollutants found in many industries and converts them to harvest low-carbon fuels using a biological enzyme. Its carbon recycling technology is like retrofitting a brewery onto an emission source like a steel mill or a landfill so that bacteria can convert carbon into fuels and chemicals . Specifically, its bio-recycling technology transforms captured waste CO/CO_2 into ethanol. While LanzaTech is already commercializing its carbon monoxide to ethanol-based process, CO_2 to ethanol is still under development.

Case study

1 Deep Branch

- **Overview:** Based in the UK, Deep Branch uses clean and renewable carbon and energy sources to create ingredients for a more sustainable food system such as their first product, Proton™, a single cell protein developed for the animal feed industry.
- **Business model:** Deep Branch's products are targeted for the protein concentrates market for animal feed, which is expected to grow beyond the next decade. Strategic partnership with BioMar, a leading supplier of aquaculture feed driving the uptake of sustainable feeds.
- **Technology:** Proprietary gas fermentation platform, (R)evolve, uses carbon dioxide and hydrogen as clean and renewable carbon and energy sources to create ingredients; pilot scale plant has been operational since April 2023. Deep Branch's products require no arable land and minimal water and as such they are up to 60% less carbon intensive than conventional proteins.

CHAPTER THREE

An outlook for CCU across markets

To realize the market potential of the four promising pathways covered in this study, regulatory enablement will play a significant role:

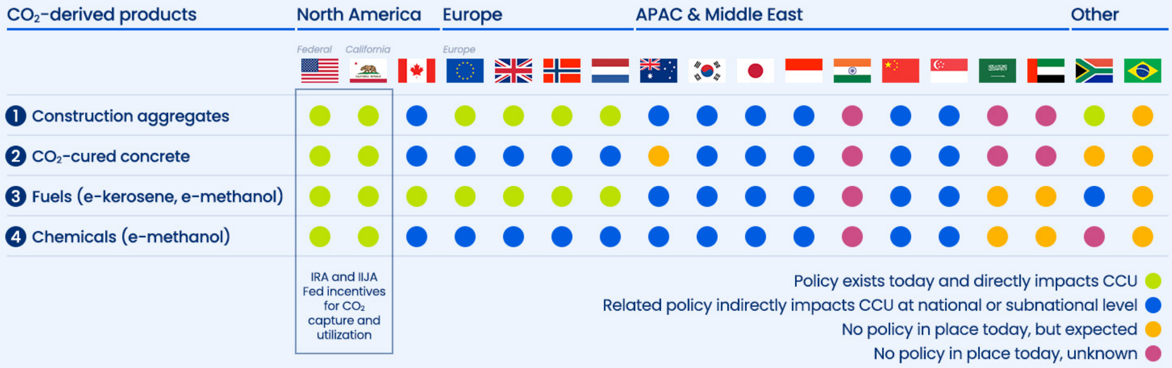
Construction aggregates	**CO_2-cured concrete**	**E-kerosene**	**E-Methanol**
• Advocate for landfill taxes • Encourage updates to rules limiting waste use	• Encourage updates to old building codes/regulations where tech is proven safe	• Encourage and implement targets (e.g., Fitfor55 EU) and advocate for implementation of global carbon pricing for shipping (starting in Europe) • Encourage/incentivize corporate procurement (e.g. Maersk leading the way on e-methanol) • Help shape public procurement programs (e.g., defence sector) • Advocate for incentives to develop renewable energy sources/green H_2 in markets that require additional regulatory support • Encourage regulation/incentives for CO_2 content in chemicals sector (carbon border taxes may put pricing pressure)	
• Help shape public procurement programs and/or targets to increase demand for low-carbon building materials • Encourage the development of harmonized accounting rules on offsetting and selling carbon (removal) emissions • Become early adaptors of key CCU technologies (e.g., working with new players) to drive down costs			

The examples above are a subset of the types of policies/regulatory levers required to make CO_2-derived products both economical and feasible. Several countries now have policies and regulatory frameworks in place for the development of CCUS, but most are focused on carbon capture and/or storage rather than specifically on utilization pathways.

Beyond policies that specifically target CCUS, indirect policies such as carbon taxes, emissions trading schemes, tax credits, etc., can also enable the growth of CO_2 utilization markets. Exhibit 6 provides an overview of some of the key markets that include policies today or are poised for CCU growth in the future, given either interest or strong fundamentals.

EXHIBIT 6

Many key CCUS geographies have indirect policies such as a carbon price, but only a few where policies are starting to emerge directly impacting CCU



CO_2-derived products	North America			Europe				APAC & Middle East									Other	
	Federal 🇺🇸	California	🇨🇦	Europe 🇪🇺	🇬🇧	🇳🇴	🇳🇱	🇦🇺	🇰🇷	🇯🇵	🇮🇩	🇮🇳	🇨🇳	🇸🇬	🇸🇦	🇦🇪	🇿🇦	🇧🇷
❶ Construction aggregates	🟢	🟢	🔵	🟢	🟢	🟢	🟢	🔵	🔵	🔵	🔵	🟣	🔵	🔵	🟣	🟣	🟢	🟠
❷ CO_2-cured concrete	🟢	🟢	🔵	🔵	🔵	🔵	🔵	🟠	🔵	🔵	🔵	🟣	🔵	🔵	🟣	🟣	🟠	🟠
❸ Fuels (e-kerosene, e-methanol)	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🔵	🔵	🔵	🔵	🟣	🔵	🔵	🟠	🟠	🔵	🟠
❹ Chemicals (e-methanol)	🟢	🟢	🔵	🔵	🔵	🔵	🔵	🔵	🔵	🔵	🔵	🟣	🔵	🔵	🟠	🟠	🟣	🟠

IRA and IIJA Fed incentives for CO_2 capture and utilization

Policy exists today and directly impacts CCU 🟢
Related policy indirectly impacts CCU at national or subnational level 🔵
No policy in place today, but expected 🟠
No policy in place today, unknown 🟣

Note: Other US states with LCFS include Washington and Oregon; several other states considering policy
Source: BCG CCUS Regulatory Database, Global CO_2 Initiative

There are several markets that already have strong policies/regulations both directly and indirectly related to CCUS. These are likely to see growth of CO_2 utilization as well:

- **EU** - Several demand-side policies and regulations are in place enabling CCU markets indirectly. These include mandates on e-fuels (FuelEU, Fit for 55), ETS/carbon price, updated RED III requiring use of renewable fuels of non-biological origins (RFNBOs) by 2034, and binding sector targets. Furthermore, emissions converted to stable materials through mineralization for example, are already exempt from ETS in Europe. Several countries have landfill taxes and 100% of new buildings must be net zero by 2030 (Fitfor55).

- **US** - Significant federal supply side incentives are in place through the Inflation Reduction Act and Infrastructure Investment and Jobs Act that provide specific credits for utilization as well as the stackable 45Z tax credit that incentivizes low-carbon fuels. Limited carbon pricing (only in selected states). IRA credit for H_2 also indirectly enables several CCU technologies and pathways by reducing the levelized cost of hydrogen required to produce e-kerosene and e-methanol.

- **UK** - CCUS policies thus far have been focused primarily on carbon capture and storage rather than utilization. The UK plans to implement a sustainable aviation fuel mandate from 2025 and already has high landfill taxes that enable the economic viability of construction aggregates. The UK has also set up a Net Zero Building Council that could eventually set targets or standards for low-carbon building materials.

- **Canada** - Heavy support for CCUS through investment tax credit and several province-level low-carbon fuel standards as well as a federal fuel charge. The government has recently confirmed an escalation of the carbon pricing scheme to reach ~$125/tCO$_2$ annually by 2030.

In several other countries CCUS policies are either emerging or there are other factors that make conditions conducive for CO_2 utilization (e.g., low-cost RES, existing production facilities for conventional products, etc.). There are several markets to be observed for CCUS regulatory frameworks and the development of CCU pathways:

- **China** - CCUS policy framework is under development and carbon pricing mechanism is already in place for specific sectors, although prices are currently low. There are varying taxes on pollution/waste as well as some regulations for buildings and embodied emissions through the General Code for Building Energy Conservation and Renewable Energy Utilization. Focus in 2020s is CCUS specifically for coal power.

- **India** - CCUS legislation is currently underway and there is potential for the development of CCUS hubs. Government incentives and policies are in place to drive investments in renewable energy sources to produce H_2, as well as specific policies and a production target for green H_2. India's central government recently authorized the establishment of a domestic carbon credit trading scheme, which could be an enabler going forward. India is a critical market for building materials but currently does not have many policies in place; however, the country is likely to design more policies in the building materials market in the future.

- **Singapore** – The government has set targets for carbon capture and there is already a carbon price in place. The Singaporean Sovereign Wealth Fund has also announced a specific fund dedicated to e-fuels.

- **South Africa** - While legislation around CCUS is lacking today, the market has strong fundamentals for renewable energy and thereby low-cost H_2 production. This could be a strong market for CCU, especially as Sasol is an e-fuels leader.

- **Japan** – An ETS is currently in its first phase and is planned for launch in 2026. The country has already put in place a CCUS roadmap despite the limited domestic storage capacity. In order to meet decarbonization targets, Japan will either have to look at CO_2 use opportunities or at exporting its CO_2 to other APAC markets.

- **Some Middle Eastern countries (e.g., Saudi Arabia, Morocco, Egypt)** - No/limited CCUS policies currently in place but are markets that have access to low-cost renewable energy and are thinking actively about and starting to invest in transitioning from hydrocarbons to carbon-based products. CCU used within industrial cities where sources of fossil CO_2 are close to industries requiring CO_2 feedstock.

- **South American countries (e.g., Chile, Brazil, Colombia)** - Currently limited CCUS policies currently in place, but potential for growth in renewables (especially solar PV and onshore wind) at competitive prices could mean potential for green H_2-based carbon products.

CHAPTER FOUR

Realizing the potential of utilization

CO_2 use has the potential to reduce the carbon footprint of many of the products that we use today, contributing to overall emissions reduction. There are five key enablers that will determine the future prospects for CCU:

1. Targeted policy incentives and the right regulatory framework, for example, public procurement targets for CO_2-based products.
2. Reduced technology costs for each utilization pathway with proven positive carbon impact.
3. Availability of CO_2 capture and transport infrastructure.
4. Access to low-cost renewable power in key markets.
5. Clear methodology around accounting for utilization of carbon (e.g., depending on the source and whether it is reemitted).

The market for CCU is expected to remain relatively small in the short term, but there is scope for corporations, governments, and other key stakeholders to support research and development of technology and to start investing early to build the required markets.

CCU can be a decarbonization lever in the medium to longer term, but it is critical that the right set of inputs and technology are leveraged in the processes used to create CO_2-derived products that support climate goals. **It is important to note that even with the right set of inputs and technology, CCU alone is not enough to meet global decarbonization goals and is not a substitute for storage. While it can be a decarbonization lever, it cannot build a circular carbon economy on its own.**

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Not exhaustive, but representative of all key materials used in addition to proprietary BCG analysis, expert interviews, and prior case experience

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