circular carbon
economy

04

Reuse:
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G20 Circular Carbon Economy Guide Report

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Executive Summary

Using or recycling CO_2 can play an important role in a circular carbon economy, transforming emissions into products with smaller carbon footprints and supporting emission reductions across the energy system. At the Osaka Summit in 2019 G20 leaders acknowledged the opportunity for innovation in carbon recycling and for "emissions to value" to support clean energy transitions.

A major expansion of CO_2 use will require the advancement of new technologies and applications. Around 230 Mt CO_2 are used each year, including in fertiliser production, enhanced oil recovery, and food and beverage manufacturing, but the growth potential for these mature applications is limited. New technologies to convert CO_2 into fuels, chemicals and building materials offer large-scale opportunities for future CO_2 use.

The use of CO_2 in fuels and chemicals is closely linked with the scale-up of low-carbon hydrogen production. These applications involve combining CO_2 with hydrogen to create a fuel or a chemical intermediate (including methane and methanol) that is compatible with existing infrastructure. CO_2-based fuels could be particularly valuable in the aviation sector, where both electrification and direct use of hydrogen is challenging. Producing synthetic hydrocarbon fuels and chemical intermediates is energy-intensive and currently expensive. For example, replacing 1% of today's oil production with synthetic hydrocarbon fuels would require almost 1 000 TWh of electricity (more than 4% of global electricity in 2018) at a cost of between USD 200/bbl and USD 600/bbl, depending on the electricity price. CO_2 use in the production of niche chemicals, such as specific plastics and baking soda, is less energy-intensive, but the market is relatively small.

Using CO_2 in building materials is less energy-intensive and can provide a form of CO_2 storage. Early commercial opportunities to use CO_2 to cure concrete or in the production of aggregates are already being realised, in some cases demonstrating improved cost and product performance relative to conventional production. The CO_2 used in building materials is retained or stored in the product, rather than being re-emitted, with further climate benefits derived from lower cement input in the case of CO_2-cured concrete.

Verification of emissions reductions will be central to establishing the role of CO_2 use in climate mitigation. The climate benefits of CO_2 use are not guaranteed and can be complex to quantify. They will be determined by a range of factors, including the source of CO_2, the amount and type of energy used, whether the CO_2 is re-emitted and if the product is displacing an alternative with a larger carbon footprint (e.g. conventional fossil fuels). Robust accounting and measurement will be required to verify the emissions reduction potential of applications using CO_2 and to inform policy and investment decisions.

The carbon management potential of CO_2 use will also be determined by the size of future markets for CO_2-based products and the development of supply chains. Near-term barriers to the expansion of CO_2 use could include constraints on the availability of key inputs, particularly CO_2 and low-carbon hydrogen (or energy), as well as the need to update existing product standards or regulations in some cases. The current high cost of many CO_2-based products relative to incumbent options will make market penetration very challenging in the absence of policy support.

Policies to promote CO_2 use should consider both supply and demand for CO_2 within a circular carbon economy. A range of policy options are available to grow CO_2 use opportunities, including measures to stimulate demand for CO_2-based products through public procurement, mandates or direct incentives. Complementary measures to incentivise the capture of CO_2 from industrial or power facilities (fossil or biomass-based) or directly from the air could also boost its supply for both CO_2 use applications and for geological storage (i.e. “Remove”).

Continued innovation will be critical to reduce costs and enable CO_2 use to contribute to future net-zero emission energy systems. In the transition to an economy with net-zero CO_2 emissions, the CO_2 used in fuels and chemicals production would increasingly need to be sourced from sustainable biomass or the air (through direct air capture). RD&D support for these applications will be important to reduce costs and accelerate their commercial availability.

Recommendations

G20 governments can target opportunities to expand CO_2 use in the short term, while laying the foundation for large-scale use in the future through innovation. Four priorities are identified:

1. **Improve the understanding and quantification of the climate benefits of CO_2 use.** Quantifying the climate benefits of CO_2 use is complex but will be important to inform future policy and investment decisions. This requires life-cycle analyses based on clear methodological guidelines and transparent datasets. Policy support should be linked to a robust emissions accounting and measurement, reporting and verification framework to validate climate benefits of CO_2 use. Governments could establish international working groups with experts to facilitate knowledge-sharing, development of standards and best practice guidelines.

2. **Increase the availability of captured CO_2.** Incentivising CO_2 capture will boost CO_2 supplies and secure a key input for CO_2-based products. More than 32 billion tonnes of CO_2 are emitted from energy-related processes each year: almost all of this will need to be avoided (the "reduce" part of the circular carbon economy approach) but some CO_2 can be captured for use, including at relatively low cost (from USD 15/CO_2). Advancing CO_2 capture from biogenic and atmospheric sources will be important for CO_2 use in the long-term, particularly in a net-zero emissions energy system. Development of shared infrastructure can enable rapid scale-up of CO_2 use in parallel with CO_2 storage.

3. **Create demand for CO_2-based products through public procurement.** CO_2 governments are major purchasers of fuels, chemicals and building materials. Procurement guidelines that value low-carbon products, including those produced with CO_2, can create early markets for CO_2 use and assist in the establishment of technical standards and specifications. Procurement guidelines should be underpinned by robust emissions accounting and MRV frameworks to ensure climate benefits are realised.

4. **Support innovation for future uses of CO_2 use that could play a role in a net-zero economy.** This includes aviation fuels and chemicals, in conjunction with RD&D for low-carbon hydrogen production and CO_2 capture from biomass and the air. In the context of Covid-19, supporting RD&D of key CO_2 use applications within economic recovery packages could help to accelerate the availability of these options consistent with their anticipated future role in meeting energy and climate goals.

01

Introduction

Introduction

The Saudi Arabia Presidency of the G20 has developed the concept of the circular carbon economy. This concept incorporates four R's, which form the basis for the transformation of energy systems from existing linear structures to more circular systems. The four R's (reduce, reuse, recycle and remove) serve as categories of mitigation options (Williams, 2019).

The reuse of CO_2 can play a key role in a circular carbon economy approach, by transforming emissions into valuable products that in turn can contribute to emissions reductions across the energy system. Captured CO_2 can be used to produce synthetic fuels, chemicals and building materials (cement and concrete) with a smaller carbon footprint than those currently in use today: effectively enabling a major source of our climate problem to be part of the solution.

There are already many well-established uses of CO_2, including in food and beverage production, refrigeration, fire suppression, water treatment and healthcare, but by far the largest current uses are in fertiliser production and enhanced oil recovery (EOR). Incremental growth in these sectors is expected but a major expansion in CO_2 use and recycling would rely on the advancement of emerging technologies and applications.

These emerging technologies apply chemical and biological processes to convert CO_2 – a very stable molecule – into fuels, chemicals, building materials and other products. This conversion process is highly energy intensive and currently expensive for most applications, although early opportunities are already being realised. The use of CO_2 in synthetic fuels and chemicals will inexorably be linked with the scale-up of low carbon hydrogen production.

The opportunity for CO_2 use and recycling also comes with caveats related to the potential climate benefits. The use of CO_2 in itself does not guarantee emissions reductions: the energy used in the conversion process, the source of the CO_2 and whether the CO_2 is re-released or retained in the product will all be important considerations in assessing the ultimate climate impact.

This report provides an overview of the current status and potential for CO_2 in key applications: fuels, chemicals and building materials. It considers barriers to scaling up these applications and identifies policy priorities for G20 countries.

02

Current status: CO_2 use today

Current status: CO_2 use today

How can CO_2 be used?

CO_2 can be used as a valuable input to a range of products. The potential applications for CO_2 include direct use, where the CO_2 is not chemically altered (non-conversion), or the transformation of CO_2 to a product (conversion) (Figure 1).

Most existing commercial applications involve direct use of CO_2, including the production of food and beverages and the injection of CO_2 in oil reservoirs to enhance oil recovery (see next section). These applications make use of several properties of CO_2, including its large heat absorption capacity, stable and non-reactive nature, and its ability to act as a solvent.

The conversion route has sparked considerable interest in recent years, resulting in the advent of multiple CO_2 use projects around the world (Table 1). There are a large number of emerging technologies applying chemical and biological processes to convert CO_2, many of which are still in an early stage of development but may become commercially available in the future. Three novel or emerging applications for CO_2 use are:

- **Fuels:** the CO_2 is reacted with hydrogen to create a fuel that is as easy to handle and use as gaseous or liquid fossil fuels.
- **Chemicals:** the carbon in CO_2 is used as an alternative to fossil fuel in the production of chemicals. Many chemicals require carbon to provide their structure and property.
- **Building materials:** the CO_2 is reacted with minerals or waste streams, such as iron slag, to form carbonates for building materials. This conversion pathway involves the permanent storage of the CO_2 in the materials.

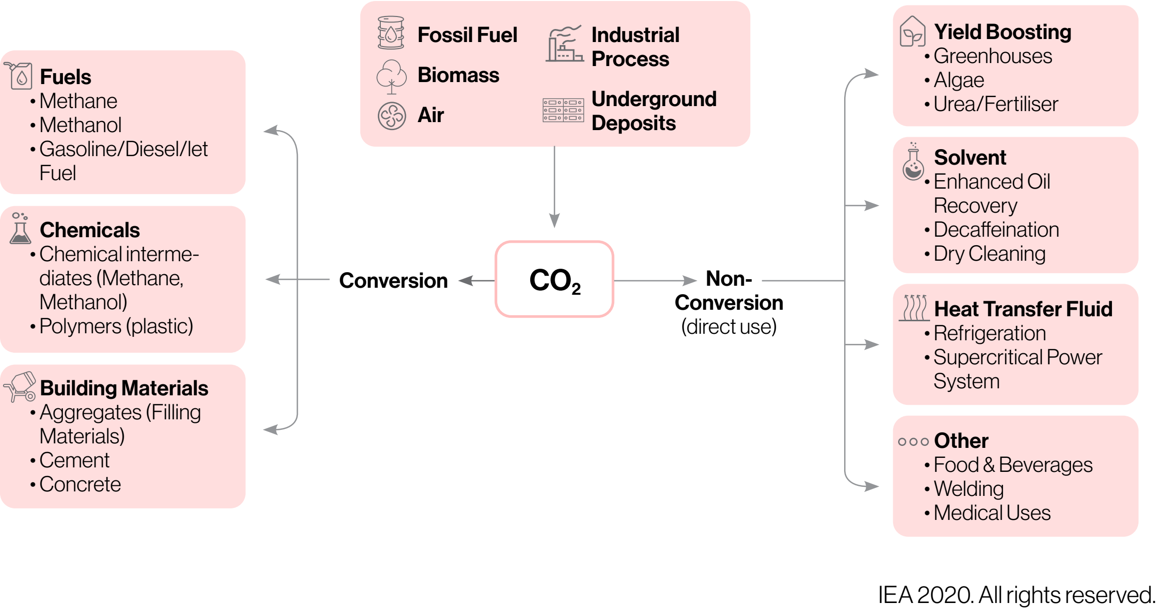

Figure 1. Simple classification of CO_2 use pathways.

CO_2 can be used in a broad range of applications involving direct use of CO_2 or use through conversion into fuels, chemicals and building materials.

Table 1. Select CO_2 use projects and technologies

	Country	Project	Operation date	CO_2 use application	CO_2 use capacity ($ktCO_2$/year)	CO_2 source
Building materials	United Kingdom	Carbon8 Suffolk and Avonmouth facilities	2012	Building materials - Aggregates from waste	5.6 (across two facilities)	Nearby bio-ethanol plant (Suffolk plant)
	United States	Solidia Technologies and EP Henry at Lafarge Holcim Whitehall plant	2014	Building materials - CO_2-cured concrete	NA	NA
	United States	Kendeda Building for Innovative Sustainable Design with Carbon Cure and Thomas Concrete	2019	Building materials - CO_2-cured concrete	18 (total)	Fertilizer production facility
Chemical intermediates and plastics	United States	Searles Valley Minerals (Trona soda ash plant)	1976	Chemicals - Soda ash	270	Coal-fired power generation
	Australia	Alcoa Kwinana Carbonation Plant	2007	Carbonation of residue from aluminium production	70	Ammonia plant
	Canada	CleanO2 carbon capture technologies	2013	Chemicals - Soaps	9 (per unit)	Natural gas-powered boilers in commercial buildings
	United States	Carbon Free Chemicals and Capitol Aggregates' Skymine® plant	2015	Chemicals - Soda ash	83	Cement production facility
	Japan	Saga City Waste Incineration Plant	2016	Algae cultivation	3.6	Waste incineration plant
	India	Tuticorin Alkali Chemicals & Fertilizers and Carbon Clean Solutions plant	2016	Chemicals - Soda ash, ammonium chloride fertilizer	60	Nearby 10MW coal power generation plant
	Germany	Covestro Dormagen facility	2016	Chemicals - Plastics	5	Nearby chemicals production facility
	Saudi Arabia	SABIC Carbon Capture and Utilisation Project	2018	Chemicals	500	Ethylene glycol production facility

	Country	Project	Operation date	CO_2 use application	CO_2 use capacity ($ktCO_2$/year)	CO_2 source
Fuels	Iceland	Carbon Recycling International George Olah Renewable Methanol facility	2012	Fuels	5.6	Nearby geothermal plant (by-product of steam extraction)
	Germany	Audi e-gas plant	2013	Fuels	2.8	Exhaust gas of a nearby biomethane plant
	China	Beijing Shougang LanzaTech New Energy Science & Technology Co., Ltd.	2013	Fuels	NA	Iron and steel production facility
	Canada	Carbon Engineering's Air-to-FuelsTM prototype plant	2017	Fuels	0.4	Air
	South Africa	Swayana Mpumalanga LanzaTech project	Planned	Fuels	NA	Iron and steel producion facility
TBD	India	Dalmia Cement (Bharat) Limited and Carbon Clean Solutions facility	Planned	To be determined - multiple utilisation streams	500	Cement production facility

Note: This is not a comprehensive list of CO_2 use projects; the examples shown here demonstrate a range of applications and locations of existing and planned CO_2 use projects; methanol derived from CO_2 can be used as a fuel or chemical intermediate; TBD = to be determined.

Current uses of CO_2

The global demand for CO_2 in 2015 is estimated to be approximately 230 million tonnes (Mt) of CO_2.[1] By far the greatest consumer globally is the fertiliser industry, where 130 Mt CO_2 is used in urea manufacturing, followed by oil and gas, with a consumption of 70 to 80 Mt CO_2 for enhanced oil recovery (CO_2-EOR) (Figure 2). The remaining share represents a wide range of commercial applications, predominantly in the food and beverage sector.

Today, around 33% of the global CO_2 demand comes from North America, followed by the Republic of China (21%) and Europe (16%). Global demand for established CO_2 uses is growing steadily year-on-year, with an estimated average annual growth rate of 1.7% per year through to 2022 (IHS Markit, 2018). By extrapolating this trend, the annual consumption would reach approximately 270 $MtCO_2$ in 2025.

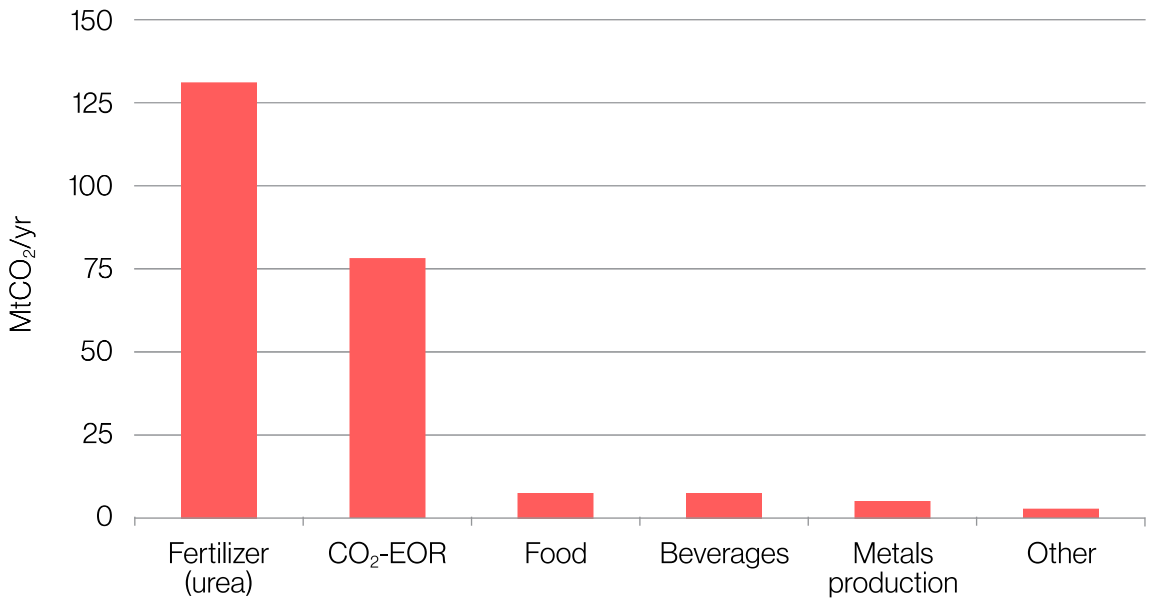

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Figure 2. Breakdown of global demand for CO_2 (2015).

Sources: IEA analysis based on ETC (2018), Carbon Capture in a zero-carbon economy; IHS Markit (2018), Chemical Economics Handbook – Carbon Dioxide, US EPA (2018), Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2016.

Global demand for CO_2 is mainly driven by fertilizer production and EOR.

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[1] This number includes both internally and externally sourced CO_2. Internally sourced CO_2 refers to processes where CO_2 is produced and captured in a chemical manufacturing process, and ultimately consumed in a later process step; the most important example is integrated ammonia-urea plants. Externally sourced CO_2 refers to CO_2 that is external to the process and needs to be captured.

Fertilizer production

The carbon-containing fertilizer urea is produced by reacting ammonia with CO_2. Most of the CO_2 is sourced from the concentrated emissions streams that arise during the ammonia production process. Ammonia and urea are often produced in integrated or co-located facilities. In rare cases, CO_2 is sourced from onsite boilers or naturally occurring underground deposits.

Urea is really only a rest stop on the road to emissions release. After the urea leaves the production plant, it is sold, stored, and then applied to the soil in order to fulfil its primary purpose – delivering the nitrogen it contains to the roots of plants and crops. The CO_2 that was embedded in the urea is then released to the soil and, as the urea decomposes, to the atmosphere.

Enhanced oil recovery

CO_2-EOR is a well-established commercial technology that has been applied since the 1970s, primarily in the United States. The technology involves the injection of CO_2 into oil fields to enhance production. This increases the overall reservoir pressure and improves the mobility of the oil, resulting in a higher flow of oil towards the production wells.

Today the majority of CO_2 injected in CO_2-EOR projects is produced from underground CO_2 deposits; for example, in the United States where most CO_2-EOR occurs, more than 70% of the CO_2 used is derived from non-geological sources. The remainder comes from anthropogenic sources, such as natural gas processing facilities and bioethanol plants. The CO_2-EOR industry is facilitated by an extensive pipeline infrastructure of over 7000 km (NETL, 2015). Other countries applying CO_2-EOR, but on a smaller scale, include Brazil, Canada and China. The cost of CO_2 is generally linked to the oil price and can range from around USD 15-30/tCO_2: injecting 0.5 CO_2/bbl oil would therefore cost around USD 7.5-15/bbl (IEA, 2018a). CO_2-EOR has the potential to deliver climate benefits (Box 1).

Globally, an estimated 190-430 billion bbl of oil are technically recoverable with CO_2-EOR. This would require injecting between 60 and 390 billion tonnes of CO_2 (IEA, 2015): for comparison, total global energy-related CO_2 emissions are currently around 32 billion tonnes each year. The United States has the greatest potential, but there are also good prospects in Central Asia, the Middle East and Russia. Today, the key obstacles to wider deployment are high capital outlay for projects, suitable geology, lack of CO_2 transport infrastructure and limited availability of low-cost and reliable sources of CO_2 in close proximity to oil fields.

Box 1: How can CO_2-EOR deliver climate benefits?

While CO_2-EOR is primarily pursued to boost oil production, it has the potential to deliver climate benefits as well. During the process, a portion of the CO_2 remains underground, while the remainder returns to the surface as the oil is extracted. Most CO_2-EOR projects recycle CO_2 returning to the surface as it is an expensive input to the production process, resulting in over 99% of the injected CO_2 being permanently stored over the life of the project.

Today, between 0.3 and 0.6 tCO_2 is injected in EOR processes per barrel (bbl) of oil produced in the United States, although this varies between fields and across the life of projects (IEA, 2018a). Given that a barrel of oil releases around 0.4 t CO_2 when combusted, and around 0.1 tCO_2 on average during the production, processing and transport of the oil, this opens up the possibility for the full lifecycle emissions intensity of oil not only to be lower than those of conventionally produced oil, but even to be “carbon-negative”.

This can only be achieved if a non-fossil source of CO_2 is used and the amount of CO_2 stored exceeds the emissions from the production and combustion of the oil itself. In other words, to produce “carbon-negative oil” – that is for CO_2-EOR actually to reduce the stock of CO_2 in the atmosphere – the CO_2 either has to come from the combustion or conversion of biomass or has to be captured from the air.

Other commercial uses of CO_2

In addition to fertilizer and oil production, some 20 to 30 $MtCO_2$ per year is used in a large variety of smaller-scale applications. Around half of this is used in the food and drink sector, primarily in beverage carbonation, and to a lesser extent in food freezing, decaffeination of coffee, chilling and packing applications. Other applications of CO_2 use include metal working, cooling, fire suppression, water treatment, healthcare, dry cleaning of textiles and in greenhouses to stimulate plant growth. Although demand for CO_2 is growing year-on-year, the total potential for CO_2 use in these applications is limited.

Sources and price of CO_2

The CO_2 used today is predominantly sourced from industrial processes that produce high-purity CO_2 as a by-product, such as ammonia production and biomass fermentation, or extracted from natural underground CO_2 deposits (mainly for EOR purposes). Supply per industrial source may be in the order of 10 000 to 500 000+ tonnes of CO_2 (tCO_2) per year, with individual non-EOR customers typically requiring relatively small volumes (US EPA, 2018).

The price of CO_2 is usually determined through negotiations between suppliers and consumers and tends to differ considerably per region and industry. CO_2 from ammonia producers can yield a price ranging from USD 3 to USD 15 tCO_2 under long-term contracts, while prices for niche markets with small volumes and a high degree of purity can be USD 400/tCO_2 or even much higher (GCCSI, 2011; CarbonCure, 2018).

03

Emerging opportunities for CO_2 use: Technology and cost performance

Emerging opportunities for CO_2 use: Technology and cost performance

Opportunities to use CO_2 in the production of fuels, chemicals and building materials have gained significant interest in recent times. These applications could technically enable the use of large quantities of CO_2 in the future, but most are currently at an early stage of development.

Fuels

Technology

CO_2 can be used to produce many of the fuels available on the market today, such as methane, methanol and liquid fuels (e.g. diesel or aviation fuels). The use of these so-called synthetic hydrocarbon fuels [2] in existing infrastructure is typically easier and cheaper than transporting and storing electricity and hydrogen. The production of synthetic hydrocarbons fuels is very energy-intensive. Unlike the chemical compounds making up fossil fuels, CO_2 is a very stable, non-reactive molecule with a low energy state, meaning that large amounts of external energy must be supplied to convert it into an energy-rich fuel. The most mature conversion pathways use energy in the form of hydrogen.

The following products and conversion pathways are most technologically mature (Figure 3):

- **Synthetic methane:** This can be directly produced from CO_2 and hydrogen in a technologically mature methanation process. Today, some 70 demonstration plants producing synthetic methane are in operation, most of them located in Germany and other European countries. In Werlte in Germany, for example, a plant with an electrolyser capacity of 6 MWe has been producing 300 m^3 per hour of synthetic methane since 2013, with CO_2 being provided by a biogas plant (Audi, 2019).

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[2] Fuels made from CO_2 and energy can be referred to in several ways, including CO_2-based fuels, carbon fuel carriers, synthetic hydrocarbon fuels and electrofuels. In this report, the term synthetic hydrocarbon fuels is used.

- **Synthetic liquid fuels:** In the production of synthetic liquid fuels, CO_2 is first converted into CO, after which it is (together with hydrogen) synthesised into raw liquid fuels and, with further upgrading, into synthetic diesel or kerosene. The conversion from CO_2 to CO has been successfully demonstrated on a small scale, while the fuel synthesis process is technologically mature. Several companies have operated pilot plants producing liquid fuels from CO_2. Sunfire GmbH is currently developing an industrial-scale plant in Norway that will have a production capacity of 10 million litres or 8 000 tonnes per year of synthetic crude oil (Sunfire, 2020).

- **Synthetic methanol:** Similar to methane, methanol can be produced directly from CO_2 and hydrogen through a process called hydrogenation. Alternatively, methanol can be made from hydrogen and carbon monoxide via the methanol synthesis processes. The production of methanol from synthesis gas is fully commercial. Over the past decade, several firms have built demonstration plants (Box 2).

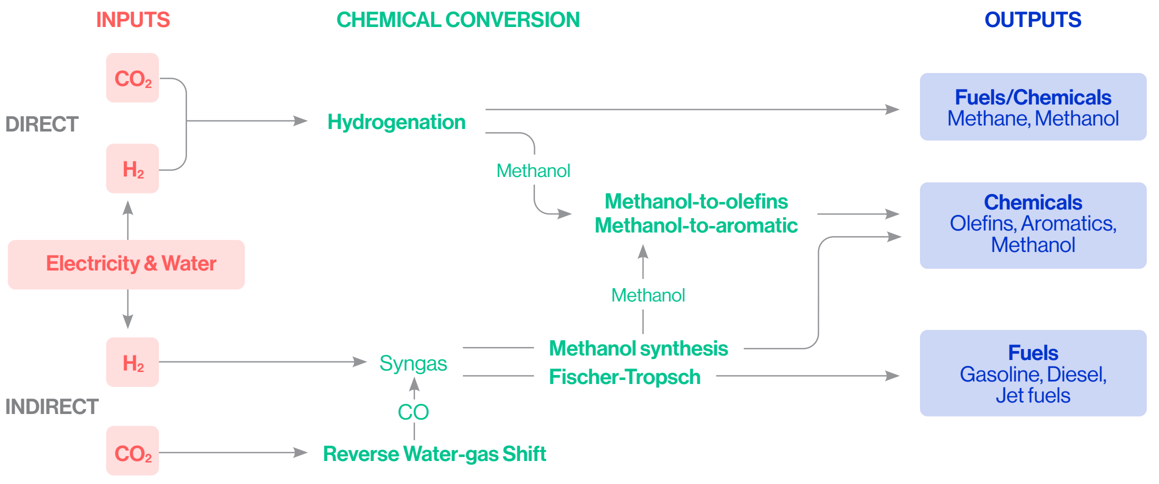

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Figure 3. Mature conversion route for synthetic hydrocarbon fuels and chemical intermediates

CO_2 can be used to produce fuels and chemical intermediates through several conversion routes, but these require significant energy input.

If the hydrogen is produced from electricity, the overall conversion efficiency of the production process is around 50%, but this differs per type of product (Figure 4). The CO_2 use rates are high, with methanol requiring 1.37 tCO_2 per tonne of product, methane 2.74 tCO_2 per tonne of product and kerosene 3.2 tCO_2 per tonne of product, assuming 100% conversion efficiency. Other chemical and biological conversion pathways, such as artificial photosynthesis, are still in the early stages of their technological development.

Significant amounts of electricity and generation capacity are required for the production of synthetic hydrocarbon fuels because of the low overall efficiency of production processes. Around 1 000 TWh and 700 TWh of electricity would be needed as input for synthetic hydrocarbon fuels to provide just 1% of current global oil and global gas production respectively, representing around 4% and 3% of global electricity generation in 2018. This would require 600 GW and 400 GW of solar PV capacity at a capacity factor of 20%, or 340 GW and 230 GW of onshore wind capacity at a capacity factor of 35%.

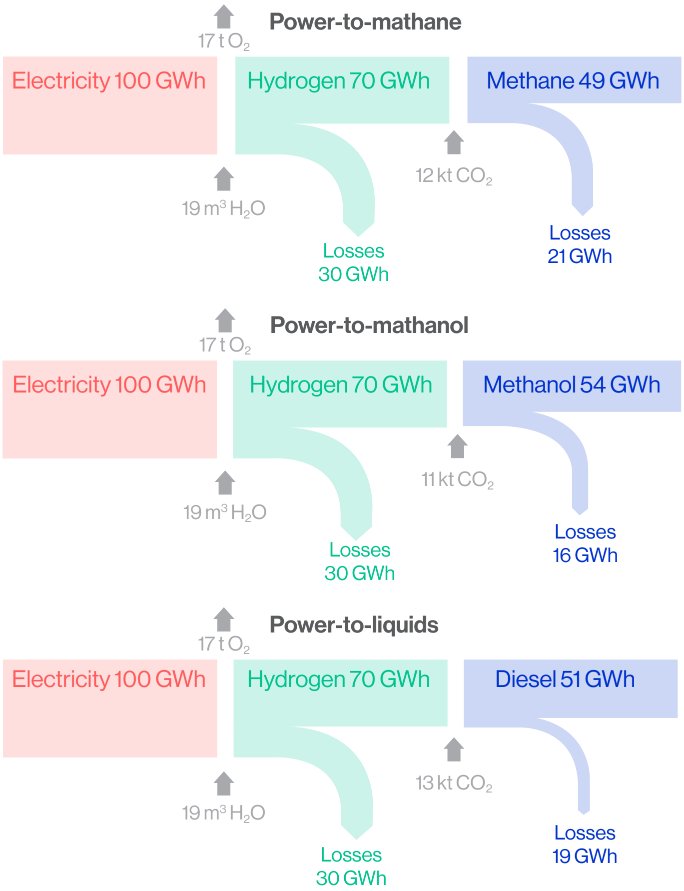

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Figure 4. Conversion losses during production of synthetic hydrocarbon fuels.

Around 45-60% of the electricity used for the production of synthetic hydrocarbon fuels is lost during the conversion processes.

Box 2: Demonstration plants producing synthetic methanol from CO_2 and hydrogen

Several firms have built demonstration plants producing synthetic methanol from CO_2 and electrolytic hydrogen.

The largest plant is the George Olah Renewable Methanol facility in Svartsengi, Iceland. The facility, built by Carbon Recycling International in 2012, converts around 5.6 kt of CO_2 per year into approximately 4 kt of methanol using electrolytic hydrogen. The input electricity is generated from hydro and geothermal energy, while the CO_2 is imported from a geothermal power plant located nearby, where it is a by-product of steam extracted from geothermal reservoirs which would otherwise be vented into the atmosphere. The product, called "vulcanol", is sold on the market in Iceland and abroad where it is blended with gasoline and used in the production of biodiesel. The fuel can be produced competitively due to the availability of low-cost electricity and CO_2 (CRI, 2019).

Costs

At present, the cost of producing synthetic hydrocarbon fuels is multiple times higher than the market price in most regions in the world (Figure 5). The chief cost factor is typically energy needed for the production of hydrogen. Reducing the cost of electricity for hydrogen production is therefore an important goal, together with increasing the overall efficiency of the conversion chain.

CO_2 feedstock costs can be an important further cost component (Box 3). For example, CO_2 feedstock costs of USD 150/tCO_2 (assuming an electricity price of USD 20/MWh), corresponding to the cost of CO_2 capture from a very small and dilute source of CO2 (e.g. small industrial furnace), translate for synthetic diesel into a cost of USD 330/bbl; CO_2 feedstock costs of USD 30/tCO_2, corresponding to the cost of CO_2 capture from bioethanol, translate into a cost of USD 280/bbl. Commercial production of synthetic hydrocarbon fuels could be possible in markets where both low-cost renewable energy and CO_2 are available, such as in North Africa, Chile or Iceland.

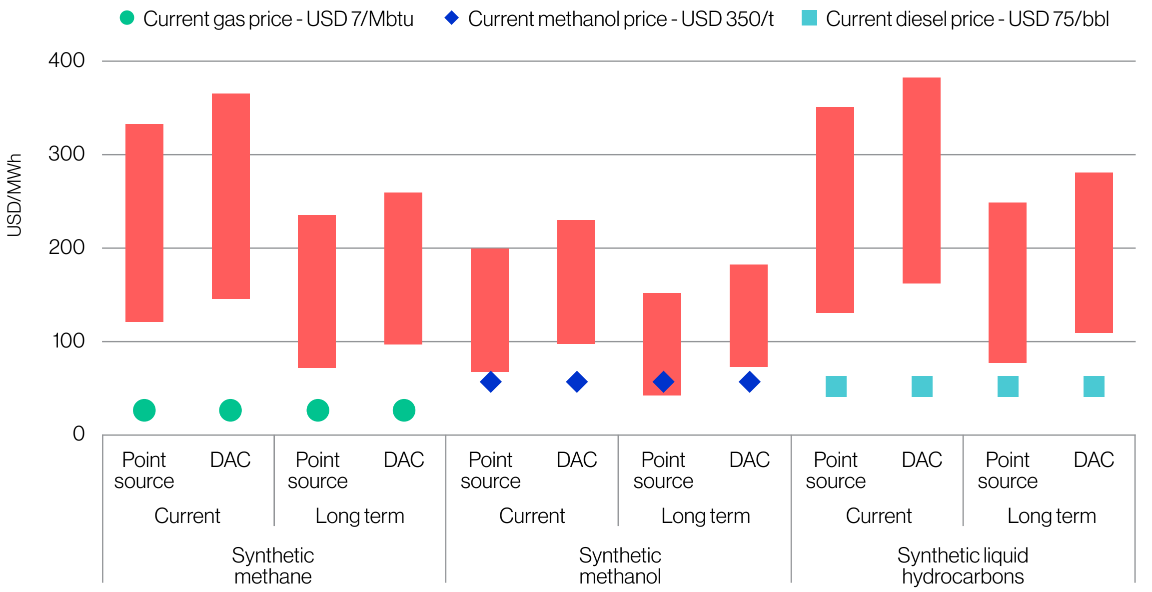

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Figure 5. Current and future levelised cost of different synthetic hydrocarbons

Notes: synthetic hydrocarbons made from CO_2 and electrolytic hydrogen. The bars represent a range in electricity prices of USD 20-100/MWh. Synthetic liquid hydrocarbons are produced via FT synthesis including upgrading. Current: 2020; long term: 2050. Based on 8% discount rate, 25 years system lifetime. Electrolysis: CAPEX USD 1036/ kWe (current) USD 402/ kWe (long term), OPEX 2.2% (current) 1.5% (long term) of CAPEX, 74% efficiency, 5000 full load hours. Synthetic methane: CAPEX USD 843/kW fuel (current) USD 564/kW fuel (long term), OPEX 4% of CAPEX, 77% efficiency. Synthetic methanol: USD 46/(tCH3OH/yr) (current and long term), OPEX 1.5% of CAPEX, electricity consumption 1.5 GJ/tCH3OH. Synthetic liquid hydrocarbons: CAPEX USD 888/kW fuel (current) USD 564/kW fuel (long term), OPEX 4% of CAPEX, 73% efficiency. CO_2 point source is from bioethanol production at USD 30/tCO_2 in the near- and long-term; CO_2 feedstock costs upper range based on DAC at USD 150/tCO_2 based in the near-term and USD 100/tCO_2 in the long-term.

Future cost reductions for synthetic hydrocarbons will depend on lowering the electricity costs, with cost reductions for CO_2 feedstocks also being critical.

Over time, production costs of synthetic hydrocarbon fuels are expected to come down, mainly due to capital cost reductions and availability of low-cost renewable electricity and feedstock CO_2. Yet, the direct use of low-carbon hydrogen and electricity as a fuel will likely continue to be a more cost-effective option in most cases. Synthetic hydrocarbon fuels may notably be used in sectors in which carbon-containing fuels will continue to play an important role, because the use of electricity or hydrogen is extremely challenging, for example in the aviation sector. Synthetic hydrocarbons will most likely continue to be uncompetitive in most regions in the absence of a stringent CO_2 price regime. If for example synthetic diesel can be produced at costs of USD 150/bbl, an equivalent CO_2 price of USD 180/tCO_2 would be needed for synthetic diesel to become competitive with fossil diesel at USD 75/bbl.

Box 3: Input costs: CO_2 and hydrogen

The price of CO_2 and hydrogen have a large impact on the production cost of synthetic hydrocarbon fuels and chemicals. Prices can vary per region for both inputs, depending on available resources and local market conditions.

The price of CO_2 is mainly determined by the cost of CO_2 capture, which varies greatly by point source, ranging from USD 15 to 60/tCO_2 for nearly pure and concentrated CO_2 streams, USD 40 to 80/tCO_2 for coal and gas-fired power plants, to well over USD 100/tCO2 for small, dilute point sources (e.g. industrial furnaces) and direct air capture (DAC).
Transport of CO_2 to the end-user can also be a significant cost, depending on the distance and transport mode (pipeline, ship). One of the appeals of DAC is that it could potentially be situated anywhere, provided there is an available energy source, thus avoiding CO_2 transport.

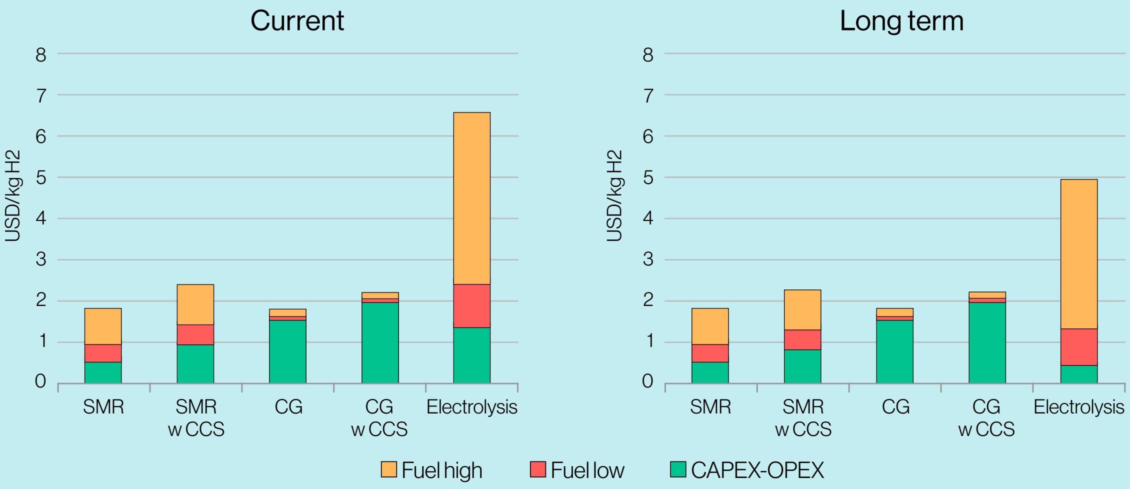
Selected CO_2 capture cost ranges for industrial production

CO_2 source	CO_2 concentration in gas stream [vol-%]	Capture cost [USD/tCO_2]
Highly concentrated CO_2 streams	96 - 100	15 - 35
Hydrogen (SMR)	30 - 100	15 - 60
Iron and steel	21 - 27	60 - 100
Cement	15 - 30	60 - 120
Power	4 - 16	40 - 80
Direct Air Capture	0.04	134 - 342

Notes: Note: CO_2 capture costs are based on the following assumptions: technical lifetime 25 years; discount rate 8%; price of fuel 7.50 USD/GJ; price of electricity 16.67 USD/GJ. Examples of highly concentrated CO_2 sources streams include CO_2 from natural gas processing, coal to chemicals (gasification), ammonia, bioethanol and ethylene oxide. CO_2 capture costs for hydrogen refers to production via steam methane reforming (SMR); the broad cost range reflects varying levels of CO_2 concentration: the lower end of the CO_2 concentration range applies to CO_2 capture from the pressure swing adsorption off-gas, while the higher end applies to hydrogen manufacturing processes in which CO_2 is inherently separated as part of the production process. Costs estimates are based on capture in the United States.

Sources: IEA analysis based on own estimates and (GCCSI, 2017; IEAGHG, 2014; NETL, 2014).

Hydrogen can be produced through a wide variety of technologies and sources. The most mature low-carbon production routes include gas and coal-based hydrogen facilities with CCS, and water electrolysis using zero-carbon electricity. Fossil fuel hydrogen production with CCS is the cheapest option in most regions today, but over time electrolysis will become increasingly competitive in regions with low-cost renewable sources.



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Levelised global average hydrogen production costs, today and in the long term

Notes: SMR, steam methane reforming. CG, coal gasification. Assumptions: 8% discount rate, 25 years system lifetime, natural gas price USD 3-9/MBTU, coal price USD 18-48/toe, electricity price USD 20-100/MWh. SMR CAPEX USD 910/kW H2 (current and long term), OPEX 4.7% of CAPEX, 76% efficiency, 95% load factor. SMR w CCS CAPEX USD 1583/kW H2 (current) USD 1282/kW H2 (long term), OPEX 3% of CAPEX, 69% efficiency, 95% load factor, 90% capture rate. CG CAPEX USD 2672/kW H2 (current and long term), OPEX 5.0% of CAPEX, 60% efficiency, 95% load factor. CG w CCS: CAPEX USD 2783/kW H2 (current and long term), OPEX 5.0% of CAPEX, 58% efficiency, 95% load factor, 90% capture rate. Electrolysis CAPEX USD 1036/ kWe (current) USD 402/ kWe (long term), OPEX 2.2% (current) 1.5% (long term) of CAPEX, efficiency 64% (short term) 74% (long term), 5000 full load hours. Electrolysis CAPEX calculated as the average of global alkaline and PEM CAPEX assuming a capacity deployment by 2050 of 1250 GW of water electrolysis.

Fossil-based hydrogen is currently the least-cost supply option, but over time electrolysis will become increasingly competitive in regions with cheap renewable sources.

Chemicals

Technology

CO_2 can be used as a raw material to produce a wide range of carbon-containing chemicals, including plastics, fibres and synthetic rubber. The carbon in these chemicals is inherent in providing its structure and properties but today this carbon is largely sourced from fossil fuels. Apart from biomass and waste, CO_2 is one of the few carbon building blocks that can be used as an alternative raw material.

The following products are most technologically mature:

- **Chemical intermediates:** CO_2 can be used to produce a number of intermediate chemicals, which can then be processed into an array of more complex chemicals. Of the intermediate chemicals that can be made from CO_2, methanol is most technologically mature and can be used to produce olefins (e.g. ethylene, propylene) and aromatics (e.g. benzene, toluene, xylene). Both are used in various applications, particularly in the production of plastics. Methanol-to-olefins technology is currently deployed at commercial scale in China, while methanol-to-aromatics technology is still in the demonstration phase.

- **Polymers:** A special group of chemicals are polymers, which are used in the production of plastics. CO_2 can be used to replace up to 50% of the fossil-based feedstock (Figure 6). The CO2 use rate per tonne product is much lower than for chemical intermediates, but this application also requires much less energy input. A number of companies are producing polymers using CO_2 (Box 4).

- **Soda ash and baking soda:** These chemicals have a so-called carbonate (CO_3) group and can be manufactured from CO_2 and salt solutions. Their production with requires less energy than intermediate chemicals. The main application of these chemicals is in glass manufacture, cleaning agents and detergents. The two largest companies are Carbon Free Chemicals (Skymine® process) and Searles Valley Minerals (Carbon Free Chemicals, 2019; Searles Valley Minerals, 2019).

Other CO_2-based chemicals, such as formic acid and dimethyl ether, are still in the early stages of development, but may prove promising in the long term (CarbonNext, 2017).
The market for CO_2-based polymers, soda ash and baking soda is relatively small. For example, to fulfil the global annual demand for soda ash and baking soda would require some 13 $MtCO_2$. The market potential for CO_2-based chemical intermediates is considerably larger. Producing all primary chemicals from CO_2 would have large implications in terms of energy, in particular for the generation of low-carbon hydrogen. Previous IEA analysis shows that around 17 000 TWh of renewable electricity, 2.3 Gt of CO_2 and 2.2 Gt of water would be needed to satisfy the global primary chemical demand with products made from CO_2 in 2030 (IEA, 2018b). To put these figures into perspective, current global electricity generation is nearly 27 000 TWh per year. The high water intensity of CO_2-based primary chemicals could be a constraint for areas with limited water availability. A careful selection of the location for electricity-based hydrogen production capacity would therefore need to consider access to local water resources.

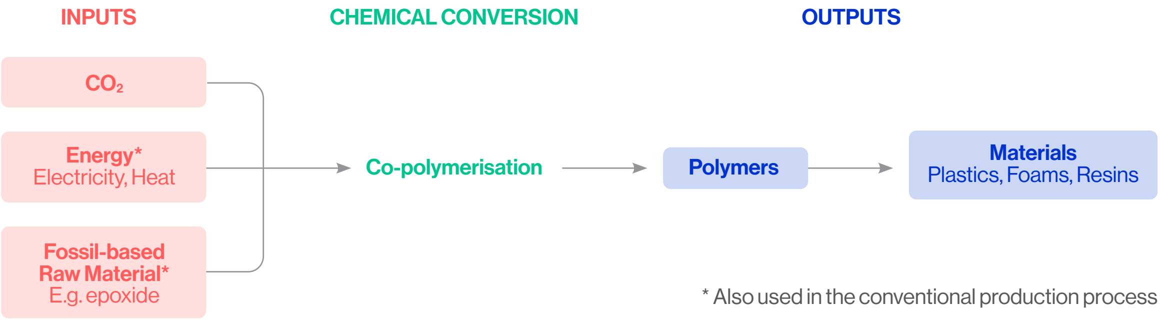

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Figure 6. Mature conversion pathway for CO_2-based polymers.

CO_2 can be converted into polymers, which can be used in a wide variety of products.

Costs

Most commodity chemicals have highly optimised production chains and low profit margins, thus making it difficult for CO_2-based chemicals to compete. As for synthetic hydrocarbon fuels, low-cost renewable electricity and significant cost reductions along the value chain are needed to make synthetic methanol competitive. Willingness to pay for CO_2 is higher than for fuels due to the higher value of chemicals per tonne of CO_2 used.

The production costs of CO_2-based soda ash and baking soda are unclear. A public study indicated production costs for CO_2-based soda are between USD 800-1500/t, which is several times higher than the market price (USD 200-350/t) (ADEME, 2014; Trading Economics, 2019).

Polymer processing with CO_2 can be competitive in the market, due to the relatively low energy required for their production and their high market value. Some claim that certain polymers called polycarbonates can be made at 15% to 30% lower cost than their fossil counterparts, provided the CO_2 used is cheaper than the fossil fuels-based raw material it replaces (von der Assen, 2015). Others have reported that the breakeven CO_2 cost, which represents the incentive per tonne of CO_2 used that would be necessary to make the pathway economic, could be as low as USD 2590/ tCO_2 (Hepburn et al., 2019). In other words, CO_2 could be used with substantial savings in production costs. However, both production costs and breakeven CO_2 cost will depend heavily on the specific application of the polymer and the market price of the final product in which it is used. Several companies have already announced that they have reached the commercialisation phase (Box 4)

Box 4: Commercial production of polymers from CO_2

A number of companies developing CO_2-based polycarbonates announced they have reached the commercialisation phase.

In 2016, Covestro commissioned a commercial plant producing 5 000 tonnes of polycarbonates per year at Dormagen, Germany. Once in operation, the facility will use CO_2 to substitute a portion of the fossil feedstock normally fed into the production process, resulting in a CO_2 content of around 20% by weight in the final product. The product will be used as a feedstock for the production of foams for mattresses and furniture (Covestro, 2018).

The company Novomer, purchased by Saudi Aramco in 2016, is due to start a commercial production facility with a capacity of 50-100 kt/yr of CO_2-based polycarbonate in 2019 in Texas, United States. The company produces polymers that contain up to 50% CO_2, which can be used in several industrial applications, such as coatings and foams (Alberici et al., 2017).

Building materials

Technology

CO_2 can be used as an input in concrete production. Concrete is a mixture of cement, water and aggregates, such as sand and crushed stone. CO_2 can be used as a component of the filler (aggregate), as a feedstock in the production of the binding material (cement), and as input in the concrete curing process. All three applications are built around the same chemical process involving the conversion of CO_2 into carbonates, which is the form of carbon that makes up concrete. This conversion pathway is typically less energy-intensive than for fuels and chemical intermediates and involves permanent CO_2 storage of the CO_2 in the materials.

The following two products are the most technologically mature (Figure 7):

- **CO_2-cured concrete:** Concrete curing refers to a series of processes that occur when water, cement and aggregates are mixed. By injecting CO_2 as part of the concrete mixing process, water is replaced by CO_2 to produce calcium carbonate. CO_2-cured concrete can have superior performance compared to conventionally-produced concrete. Two North-American companies, CarbonCure and Solidia, are leading the commercialisation of CO_2-curing technology (Box 5).

- **Construction aggregates:** These products can be produced by reacting CO_2 with waste materials from power plants or industrial processes, such as iron slag and coal fly ash, which would otherwise be stockpiled or stored in landfill. Many waste streams require pre-treatment, post-separation or extreme operating conditions (elevated pressure and temperature) to react at industrially acceptable rates, which can be highly energy-intensive (ECRA/CSI, 2017). Companies in different parts of the world are scaling up businesses using waste materials; together they consume around 75 kilotonnes (kt) of CO_2 annually. The British company Carbon8 uses CO_2 to convert air pollution control residues into lightweight aggregates (Box 5).

The CO_2 use rates for building materials is much lower than for fuels and chemical intermediates, but similar to those of some polymers (see previous Section). In the case of CO_2 curing, it is between 0.02% and 3% by weight of concrete; for construction aggregates from waste, it varies per type of waste material, with 0.07-0.25 tCO_2 per tonne coal fly ash, 0.08-0.25 tCO_2 per tonne cement kiln dust and 0.26-0.38 tCO_2 per tonne blast furnace slag (ICEF, 2017; Sanna et al., 2014). The integration of CO_2 in the production of cement itself, by reacting it with magnesium minerals or other materials, is a more complex process that is in an earlier stage of development than CO_2-cured concrete. Similarly, aggregates made from CO_2 and natural minerals are still under development and have not been demonstrated at scale.

Replacing all conventional concrete with CO_2-cured concrete has been estimated to create a demand for CO_2 of up to 1 000 MtCO2 globally today, and up to 1 200 $MtCO_2$ in 2030 (ICEF, 2017). Several estimates have been made on the global amount of CO_2 that could technically be absorbed by waste streams, mostly in the range of 100 Mt/yr to 1 200 Mt/yr (Gomes et al., 2016; ICEF, 2017; Renforth et al., 2011).

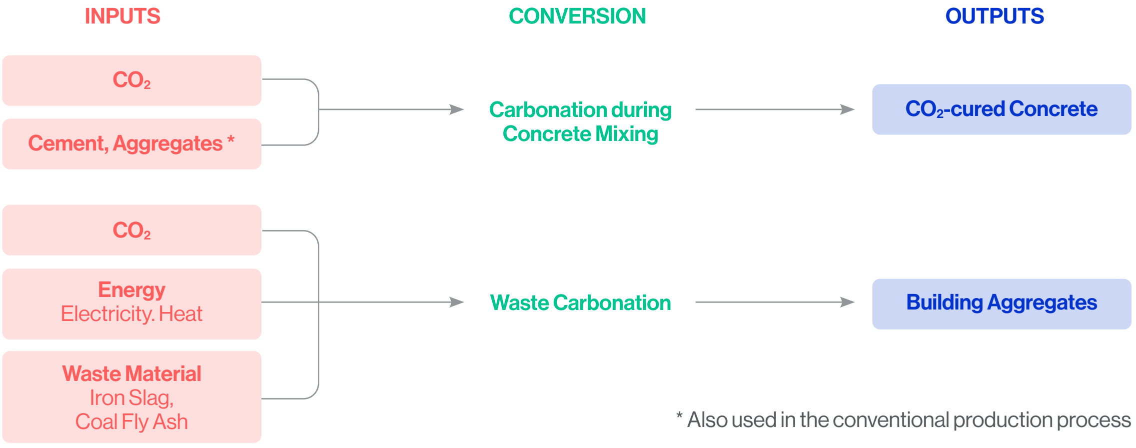

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Figure 7. Mature conversion pathway for CO_2-based building materials

CO_2-based building materials can be made from CO_2 through a carbonation process.

Costs

There is potential for CO_2 curing technologies to produce concrete with lower production costs than with conventional curing routes. The main cost savings come from lower demand for cement in the concrete mix. Some companies working on concrete curing technologies claim to be able to mitigate emissions via CO_2-curing at a CO_2 abatement cost of less than USD 6/tCO_2 (Alberici et al., 2017). Companies using CO_2 curing technology have been willing to pay a relatively high price for feedstock CO_2, mainly because relatively little CO_2 is used in the process. CarbonCure has indicated that they can make commercially viable concrete from CO_2 curing using merchant CO_2 of USD 400/t in a market with a cement price of USD 110/t (CarbonCure, 2018)[3]. While CarbonCure has been using purified CO_2, this technology may allow for the use of less pure forms of CO_2, which could further enhance the commercial viability of concrete from CO_2 curing.

Given the low market value of building aggregates, the willingness to pay for CO_2 will likely be lower than in the case of CO_2-cured concrete. In addition to aggregates made from natural minerals, carbonated waste products would have to compete with alternative waste treatment processes that can extract valuable metals for sale. Nevertheless, Carbon8 has stated that the cost for their waste-based building material is three times lower than that of other secondary aggregates [4]. In terms of CO_2 avoidance cost, a range of USD 50 to USD 300 per tCO_2 sequestered was found in literature (Sanna et al., 2014).

Early opportunities involve materials with low processing costs and locations where low-cost CO_2 and suitable waste streams exist in close proximity to potential consumers of building materials. The first markets are likely to emerge in places where these conditions exist as well as where costs of waste disposal are high. Currently, the European Union is attractive from this perspective. Examples of companies exploiting early commercial opportunities are discussed in Box 5.

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[3] This is based on a CO_2 emissions intensity of the cement of 1.04 and a CO_2 mineralisation rate 90%.

[4] Secondary aggregates" are materials which can be used as aggregate but are the waste product of another process. An example is fly ash.

Box 5: Commercial production of CO_2-based building materials

Several companies are commercially producing CO_2-based building materials today:

Canadian company CarbonCure has developed a commercial CO_2 curing process that can be easily retrofitted to conventional “ready-mix” concrete plants. Today, the technology is available in nearly 175 concrete plants (CarbonCure, 2020). CarbonCure claims that their product has better compressive strength and is more cost-effective than concrete from Portland cement. Furthermore, it claims that for every tonne of CO_2 used in CarbonCure concrete, around 254 tonnes of CO_2 can be avoided, mainly because less cement is needed per m3 of CO_2-cured concrete compared to conventionally produced concrete (CarbonCure, 2018).

The US-based company Solidia Technologies is developing both specialised cement that binds with more CO_2 (Solidia CementTM) and CO_2 concrete curing (Solidia ConcreteTM, made using Solidia CementTM) for making pre-cast concrete. Solidia CementTM must be cured in a sealed environment. Solidia reports lower costs, shorter curing times and improved product performance, while reducing the carbon footprint by up to 70% (Solidia, 2020). Several pre-cast customers in North America and Europe have been testing the Solidia’s processes. While the curing process is readily deployable, the commercial adoption of Solidia CementTM could take longer as product standards and building codes need to be updated.

The British company Carbon8 is making building materials out of waste and CO_2. Today, the firm is operating two plants producing aggregates from municipal air pollution control (APC) residues in the United Kingdom, together using 5 kt/yr of CO_2 to convert 60 kt/yr of APC residues. Both plants are located next to a concrete manufacturer that uses the Carbon8 product in aggregate blocks. Carbon8’s material is reportedly three times less expensive than most other recycled aggregates. According to Carbon8, the process fixes more CO_2 in the aggregate than it emits over its life cycle, resulting in a carbon-negative aggregate (Carbon8, 2019).

04

Carbon Management Potential

Carbon Management Potential

Can CO_2 use deliver climate benefits?

The amount of CO_2 used in a product is not the same as the amount of CO_2 emissions avoided. In fact, using CO_2 does not necessarily reduce emissions. The climate benefits associated with CO_2 use in a product arise from displacing an equivalent product with higher life-cycle CO_2 emissions, such as fossil-based fuels, chemicals or conventional building materials. The life-cycle CO_2 emissions of a product include emissions from all stages of the value chain, including upstream processes (e.g. capture and transport of CO_2), the conversion step, and downstream processes (e.g. final product consumption).

There are five key considerations in assessing the climate benefits of CO_2 use:

- **Origin or the CO_2.** CO_2 can be taken from several sources: anthropogenic CO_2 from power plants or industrial facilities, including the combustion or processing of fossil fuels or biomass; or directly from the air. Over time, the CO_2 used must be increasingly sourced from biomass or the air to close the carbon cycle and achieve "net zero" emissions (Box 6).

- **Displaced product.** The higher the carbon-intensity of the product displaced in the marketplace, the larger the climate benefits. The displaced product can differ depending on location and may change over time (for example, as the transport fuel mix becomes less dominated by fossil fuels).

- **The amount and type of energy.** This is particularly relevant for applications requiring large amounts of energy for the CO_2 conversion process, such as fuels and some chemicals, as well as for other energy-intensive steps across the life cycle, such as capture and transport of CO_2. The use of low-carbon energy is critical to minimise CO_2 emissions across the lifecycle and optimise climate benefits.

- **The carbon retention time.** In some products (building materials), carbon is permanently stored, while in other products (fuels and chemicals) the carbon is only temporarily retained and ultimately released to the atmosphere in the form of CO_2. Permanent carbon retention provides larger climate benefits than temporary carbon retention relative to the amount of CO_2 used.

- **The scale of the CO_2 use opportunity.** The potential of CO_2 use to contribute to climate goals will also depend on how far, and how fast, opportunities can be scaled up. Applications that result in emissions reductions per tonne of CO_2 used and that have a large market outlet will provide the most meaningful climate benefits.

Box 6: Why does the origin of the CO_2 matter?

CO_2 can be derived from natural deposits, anthropogenic sources or directly from the air. Not all sources of CO_2 are equally attractive from a climate perspective.

Using CO_2 from fossil energy or industrial sources, such as cement manufacturing, in the production of fuels and chemicals can deliver climate benefits as long as a higher-carbon alternative is displaced. However, the energy system would still involve fossil or industrial emissions as the CO_2 is ultimately released to the atmosphere. From an energy system's perspective, products derived from fossil or industrial CO_2 can achieve a maximum emissions reduction of 50%. This is because CO_2 can only be avoided once: either it can reduce the emissions from the fossil or industrial source or it can reduce the emissions of the final product. It cannot do both.

In the longer term, if global CO_2 emissions are to reach net zero, only non-fossil CO_2 sources could be used in applications that ultimately release the CO_2. CO_2 used for fuels and chemicals production would have to be sourced from sustainably produced biomass, such as from the production of bioethanol, or directly from the air.

In recent years, direct air capture (DAC) technologies have made significant progress: fifteen plants are currently operating in Europe and North America. Most of them are small-scale pilot and demonstration plants for CO_2 use. Two commercial plants are currently operated in Switzerland, selling CO_2 for greenhouse fertilisation and beverage carbonation, while in United States Carbon Engineering (in collaboration with Occidental Petroleum) is currently designing what could be the largest DAC facility, with a capture capacity of 1 Mt of CO_2 per year (Carbon Engineering, 2019).

The current knowledge base on the potential climate benefits of CO_2 use is relatively limited. Life-cycle assessments (LCA) show considerable variations in their findings and conclusions, meaning that policy makers and consumers face uncertainty when trying to validate CO_2 use as a viable climate mitigation tool.

Part of the variation is inherent to CO_2 use, as climate benefits can vary significantly depending on the specific circumstances, such as the carbon intensity of the input energy. But there are also other factors contributing to this variability, in particular methodological issues related to carrying out LCAs as well as limited availability of reliable data on the large-scale performance of CO_2 conversion technologies. In recent years, several organisations have sought to address these issues by developing a common LCA framework to determine climate benefits arising from CO_2 use.

Climate benefits of novel CO_2 use applications

Fuels

The climate benefits of CO_2 use in fuels can vary significantly, depending mainly on the carbon intensity of the energy and hydrogen used as well as the type of displaced product (Figure 8). Producing fuels from CO_2 does not necessarily reduce emissions. If the input hydrogen is produced from fossil fuels without CCS, or with the use of grid electricity generated at least in part by fossil fuels, the carbon footprint of this application may even be higher than that of conventional fuels. The use of low-carbon energy is therefore critical.

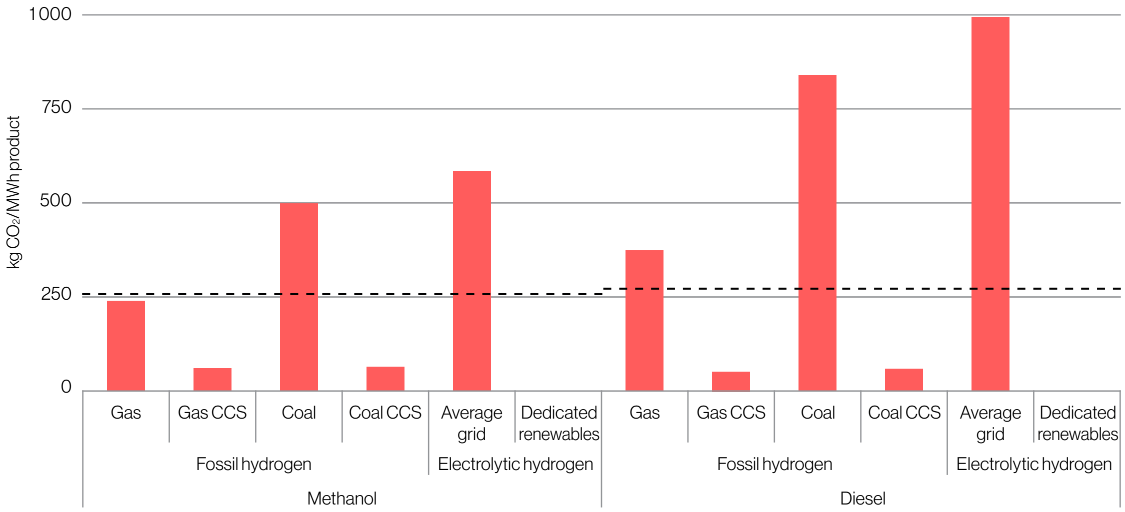

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Figure 8. Impact of energy source and hydrogen production pathway on carbon footprint of synthetic methanol and diesel.

Notes: Current 2020. Dashed lines represent CO_2 emission factor of fossil methanol and diesel. Numbers only include emissions related to energy sources; other life-cycle greenhouse gas emissions are excluded, such as emissions related to gas and coal production, energy transport, CO_2 capture, purification and transport. Dedicated renewables means the use of dedicated renewable electricity to power the electrolyser. Assumptions: efficiency (% LHV), gas 76%; gas with CCS 69%; coal 60%; coal with CCS 58%; electrolysis 64%. Electricity carbon intensity: grid 460 g CO_2/kWh (global average); dedicated renewables 0 g CO_2/kWh. CO_2 capture rate: gas CCS: 90%; coal CCS: 90%.

The use of low-carbon hydrogen is critical to achieve climate benefits for synthetic hydrocarbon fuels and chemical intermediates made from CO_2.

To determine the climate benefits, it is necessary to account for the greenhouse gas emissions across all stages of the value chain. Full LCAs show that in a best case scenario – assuming the use of low-carbon energy –, emissions can be reduced by 74% to 93% for methanol (0.5-1.0 tCO_2-eq. per t of methanol) and 54% to 87% for methane (0.03-0.05 tCO_2-eq. per t of methane) compared to fossil methanol and methane (Artz et al., 2018).

Chemicals

The potential climate benefits of CO_2 use in chemicals (synthetic methanol and methane) are similar to those as indicated for fuels.

Potential climate benefits in polymer production depend on the amount of CO_2 that can be absorbed in the material, which can be up to 50% of the polymer's mass. For example, a polymer containing 20% CO_2 by weight shows life-cycle CO_2 emissions reductions of 15% relative to the conventional production process, but larger emissions reductions are possible (von der Assen, 2015). The climate benefits of CO_2-based baking soda or soda ash have not been considered in literature.

Building materials

The use of CO_2 in concrete curing can result in a lower CO_2 footprint than conventionally-produced concrete. The climate benefits come mainly from the lower input of cement, which is responsible for the bulk of the life-cycle emissions of concrete. To date, the exact emissions reduction potential of CO_2 curing compared to conventional concrete remains unclear. CarbonCure reports that the CO_2 footprint of concrete can be reduced by around 80%, but these claims have not been verified independently (CarbonCure, 2019).

The climate benefits of CO_2 use to make construction aggregates from waste depend on the energy intensity of the production process. Pre-treatment, post-separation and extreme operating conditions (elevated pressure and temperature) can be particularly energy-intensive. Furthermore, the transport of both the heavy inputs and final products is a major contributor. The exact potential for reduction of emissions remains difficult to quantify and is case-specific. Carbon8 claims that more carbon is permanently stored during the process than emitted in its manufacture, resulting in a carbon-negative aggregate (Carbon8, 2019).

Table 2. Summary of climate benefits

Mature CO_2 use applications	GHG emissions reductions	Key efforts to maximize climate benefits
Synthetic methanol	-74% to - 95% [5]	Use of low-carbon hydrogen to achieve climate benefits.
Synthetic methane	-54% to - 87% 1	Use of low-carbon hydrogen to achieve climate benefits.
Polymers	-15%	Maximise percentage of CO_2 that can be absorbed in the material.
CO_2 curing	-80%	Minimise transport of heavy concrete and maximise CO_2 uptake in concrete.
CO_2 use in construction aggregates from waste	Unknown	Minimise transport of heavy product and optimise energy efficiency of conversion process conditions as well as the uptake of CO_2.

Sources: Artz et al. (2018), CarbonCure (2019), Carbon8 (2019).

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[5] Range comes from a review study and is due to varying assumptions made in the underlying studies

05

Outlook: The potential for CO_2 use

Outlook: The potential for CO_2 use

The future role of CO_2 use in a circular carbon economy is difficult to predict due to the early stage of technology development for many applications. Key considerations will include the size of the potential market for CO_2-based products, the technical and economic performance of these products within those markets, and the evolution of supportive policy and regulatory frameworks. This section considers first the market potential for fuels, chemicals and building materials, before identifying key barriers for deployment.

The future market for CO_2-based products

The IEA has identified three inter-related factors that will be key to determining future markets for CO_2-based products:

1. **Scalability:** While some CO_2-based products could be traded on commodity markets with huge potential demand (for example, fuels), others would target specific niche markets which could be quickly saturated (for example, polymers).

2. **Competitiveness:** CO_2-based products will be able to compete with conventionally-produced counterparts on cost and value. The cost and availability of key inputs – particularly CO_2 and hydrogen – and the energy intensity of the process will be the major determinants of economic competitiveness in the near-term.

3. **Climate benefits:** The potential to contribute to emissions reductions will be central to policy support in many regions. The climate benefits of CO_2 use are discussed in the previous section.

Table 3 provides a high-level assessment of the performance of CO_2-based fuels, chemicals (commodity chemicals and plastics) and building materials (CO_2-cured concrete, aggregates from waste) against these criteria. Fuels have the largest market potential while building materials have the strongest climate benefits per tonne of CO_2 used, in part due to the retention of CO_2 within the concrete or aggregate.

Table 3. Simplified overview of the performance of select CO_2 use applications

		CO_2 use application:				
		Fuels	Chemical intermediates	Plastics	CO_2-cured concrete	Aggregates from waste
Scalability:	CO_2 use potential (market size)	●	◐	◐	◐	◐
Competitiveness:	Economic competitiveness	○	○	●	●	◐
	Energy intensity of process	●	●	◐	○	◐
	Price sensitivity: CO_2 input	●	○	○	○	●
Scalability:	Relative climate benefits (per t CO_2 used)	◐	◐	○	●	●

Legend: ● high ◐ medium ○ low

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Notes: performance scores are generic and may differ per region and specific application. For example, some plastics are currently economically competitive in some regions and under certain circumstances. Similarly, the relative climate benefits of aggregates from waste can vary considerably on a case-by-case basis.

At a global level, CO_2 use is not expected to deliver the same scale of emissions reductions as CCS but rather is a complementary technology within the broader portfolio of emissions mitigation measures (Box 7). Previous IEA analysis has highlighted that, for every tonne of CO_2 used in fuels and fertiliser (urea) production, more than 23 tonnes would be stored in 2060 in a scenario consistent with meeting Paris Agreement climate goals (IEA, 2019). Even in a scenario where CO_2 storage is assumed to be restricted, the high CO_2 avoidance cost of most applications means that CO_2 use remains relatively modest at less than 1 Gt in 2060 (IEA, 2019).

Box 7: Understanding synergies between CO_2 use and CCS

CO_2 use is often considered together and in comparison with carbon capture and storage (CCS) in the context of climate change mitigation. While CO_2 use is not expected to fulfil the same function as geological CO_2 storage or to deliver emissions reductions at the same scale, some CO_2 use applications could contribute to emissions reductions as part of a portfolio of clean energy technologies. CO_2 use and CCS should be considered complementary technologies within this portfolio, with the potential to enable and reinforce each other's deployment. These synergies include:

- **Source of revenue:** Demand for CO_2 for productive use can provide an important revenue stream for CCS projects. The demand for CO_2-EOR has supported investment in 14 of the 19 large-scale CCUS projects currently in operation. Other emerging CO_2 use opportunities are unlikely to create demand at the same scale, but could provide a partial revenue stream for CCS projects in some circumstances.

- **Technology refinement:** Smaller-scale CO_2 use opportunities are supporting the demonstration of novel CO_2 capture routes, such as membranes and Direct Air Capture (DAC). These early demonstrations can contribute to technology refinement and cost reductions for CCS.

- **Economies of scale:** Opportunities for CO_2 use typically involve smaller streams of CO_2 demand than CCS, and can benefit from economies of scale in CO_2 capture when co-located with large-scale CCS projects.

- **Shared infrastructure:** CO_2 use could benefit from the development of large-scale capture and transport infrastructure for CO_2, especially as part of future CO_2 hubs and clusters in areas with emission-intensive industries. Such hubs and clusters can safeguard existing emission-intensive industry, while boosting novel industries pursuing CO_2 use activities, thus aligning new business opportunities with deep emissions reductions.

- **Stepping stone to CO_2 storage:** in limited cases, CO_2 use can complement CCS in places where geological storage for CCS is not accessible, ready on time or too expensive to develop for small sources of CO_2.

Barriers to deployment

There are a number of potential barriers to the early and widespread adoption of novel CO_2 use applications, including technological uncertainty, current high costs, constraints in the availability of key inputs or infrastructure, and product standards. These factors can vary significantly by region as well as by type of CO_2 use application.

The regional price and availability of key inputs, particularly CO_2 and hydrogen, have a critical impact on the technical and economic viability of CO_2 use applications. Regions endowed with good renewable resources (e.g. parts of Argentina, Australia and India) or with abundant fossil fuels and good CO_2 storage resources (e.g. Canada, Middle East and Russia), will be able to produce low-carbon hydrogen at a lower cost than regions where energy prices are higher. Similarly, the price of CO_2 is a function of regional availability of CO_2 sources (concentrated, fossil, biomass) and cost of CO_2 capture and purification. Another example is local availability of suitable waste streams that can be converted into construction aggregates with CO_2.

Implicit in the availability of key inputs is the availability of infrastructure, including transporting hydrogen and CO_2 to processing facilities. The extensive use of hydrogen and CO_2 for conversion into fuels and chemicals would require the deployment of a large-scale transport infrastructure, including pipelines and, in some places, terminals, ships and trucks. A market for CO_2 use is unlikely to emerge without these transport options already available.

In addition to these general constraints, there are several barriers related specifically to CO_2 use in the production of fuels, chemicals and building materials (Table 4). Most barriers are related to legislation, product standards and uncertainty around adequate and safe performance of CO_2-based products.

Table 4. Legal and regulatory barriers for CO_2 use in fuels, chemicals and building materials.

CO_2-based product	Barriers	Example	Measures
Fuels	• Fuel quality standards. Lengthy updating process. • Partial incompatibility with existing fuel infrastructure.	• EU Fuel Quality Directive (EC, 2020). • Synthetic methanol	• Facilitate fuel tests and updating product standards. • Retrofit / complement existing fuel distribution infrastructure. • Warranties from engine manufacturers that novel fuels are suitable.
Chemicals	• Product quality and safety standards. • Chemicals with slightly different properties. • Risk averseness of consumers to use novel products.	• Polymers with different properties (hardness, flexibility, abrasion, strength).	• Facilitate testing, and if proven safe and suitable, official approval by government agencies and updating of standards.
Building materials	• Existing standards and codes in construction sector. Updating can take multiple years. • Legislation prohibiting integration of waste in building aggregates.	• European Committee for Standardisation (CEN, 2000). • EU End of Waste Regulations (Alberici, 2017).	• Facilitate updating standards and codes. • Target applications with less strict standards and codes (roads, floors, ditches). • Revise waste regulations, if safety can be guaranteed. • Impose stricter waste disposal regulations. • Multi-year trial projects to demonstrate safe performance.

06

Enabling policies

Enabling policies

Tailored policies and incentives will be needed to improve the business case and expand opportunities to use CO_2 in the emerging pathways considered in this report. The rationale for government support is primarily based on the potential to for CO_2 use to support climate goals, however governments may also see value in stimulating industrial innovation, technological leadership and enabling the circular carbon economy.

These objectives may be well-aligned with economic stimulus goals following the Covid-19 crisis. Well-targeted support for CO_2 use could boost economic activity in the near-term – including supporting jobs and industries in key regions – while providing a foundation to meet long-term energy and climate goals through innovation. Following the 2009 global financial crisis, the United States American Reinvestment and Recovery Act provided over USD 100 million for innovative applications of CO_2 use, including research and pilot projects focused on building materials and chemical production applications (DOE, 2020).

Policy support for CO_2 use must be underpinned by robust and transparent accounting practices, including measurement, reporting and verification (MRV) frameworks, to provide confidence that emissions reductions are actually achieved. The design of such a framework is very challenging, because of the wide range of products operating in different markets and the complexity inherent in determining the emissions reductions for all of them. Governments are increasingly turning their attention to this issue, for example, with the US Internal Revenue Service publishing a proposed method for MRV under the 45Q tax credit.

Most conversion processes and CO_2-based products are at early stages of technological development and are unable to compete with incumbent products, particularly in the absence of policies that recognise and value lower-carbon alternatives. While economy-wide policy such as a carbon price could drive the market for some CO_2 use in the long term, additional, targeted policy measures are needed for the initial commercialisation phase.

Policy options to drive CO_2 use

A variety of policy instruments could be used to drive the market for CO_2 use and CO_2-based products. These measures range from demand-focused, market creation measures, mandates and incentives that directly support CO_2 use, innovation support for CO_2 use technology, or indirect instruments such as product labelling and low-carbon certification (Table 5). The suitability of policies can vary between regions and depending on the targeted application.

Table 5. Policy instruments to support CO_2 use and select examples from G20 countries

Policy instrument	Overview
Public procurement	• Leveraging the purchasing power of public procurement for lower-carbon (including CO_2-based) products can help to establish early markets, especially in sectors where government demand is significant, such as building materials and transport fuels. • Public procurement expenditure is significant, (about 12% of gross domestic product across OECD countries (OECD, 2019), and it is estimated that G20 governments spend almost a third of expenditure via public procurement (ILO, OECD and IFC, 2018). • Canada and the Netherlands have rules favouring material inputs with low-carbon footprints for construction projects. • Private companies are also important consumers of fuels and materials, and can play a role in creating early CO_2 use markets.
Mandates	• Mandates are legal requirements to bring forward products that meet certain standards or criteria, for example with policies such as the Renewable Energy Directive II (EU) and Low Carbon Fuel Standard in California favouring low-carbon transport fuels, including CO_2-based fuels. • Mandates can be used to oblige manufacturers to meet emissions criteria, or oblige firms to purchase a minimum share of products with low life-cycle CO_2 emissions.
Direct capital support	• Direct support for project capital costs can incentivise investment in CCU projects, which can have high upfront costs and long lifetimes. • Grant support has been used for early CCUS projects. • Complemented by operational support and product revenue streams, this mechanism can increase novel CO_2 uses.
Economic incentives	• Tax incentives are commonly used to advance low-carbon technologies, and could play a similar role for companies, sellers or consumers in helping to bridge the commercial gap between CO_2-based products and incumbents in the market. • Guarantees for input prices (such as Contract for Difference mechanisms) and revenue streams are also important for enabling commercial entities facing high upfront costs to establish a sound business case with an acceptable risk profile.
Product labelling	• Carbon footprint labelling is a means for individual and industrial consumers to recognise low-CO_2 products. • Labels can help to identify opportunities to lower the carbon footprint of supply chains.
Certification and testing	• Testing and certification can be required to validate CO_2-based product quality and ensure compliance. • The development of international standards for CO_2-based products is particularly important for products that require extensive demonstration and compliance with industry standards before widespread adoption, such as CO_2-based concrete and aggregates (ICEF, 2017)
Innovation support	• Support for research, development and demonstration (RD&D) should have a clear link to deployment policies. It should focus on: - Conversion technologies, including short-term opportunities such as certain building materials, and longterm applications that can play a key role in a net-zero CO_2 emission economy (e.g. aviation fuels and chemicals); - Other parts of the value chain, such as CO_2 capture technologies and low-carbon hydrogen production. - Competitive approaches such as the Canada/US hosted Carbon XPRIZE (see Box 9) and the EU Horizon Prize for CO_2 reuse

Examples of current policy support

Policies supporting CO_2 use are reasonably limited due to the relative novelty of some applications, and uncertainties in emissions accounting and MRV. However, several countries have taken measures to support the deployment of CO_2 use through financial mechanisms, including tax credits, government grants, or trading of emission credits. Others are looking into the option of using public procurement to support the uptake of CO_2-based concrete (Box 8).

A key example of existing policy with a focus on CO_2 use is the United States Section 45Q Tax Credit which provides up to USD 50/tCO_2 permanently stored, USD 35/tCO_2 used in EOR or for other beneficial uses, provided that emissions savings are clearly demonstrated. The policy applies to projects capturing emissions from electricity production, industrial facilities and direct air capture, and notably, CO_2 utilisation in industry. Such measures will likely need to be combined with other incentives to stimulate large-scale CO_2 use outside of EOR applications, particularly as the credit is adjusted based on verified emissions reductions. For fuels and chemicals, the CO_2 is ultimately released, suggesting that only a share of tax credit will be available, while concrete and carbonate materials are likely to be able to claim higher credits, but typically have lower uptake rates. However, given a surge of CO_2 capture for geological storage and EOR, firms seeking early opportunities to integrate CO_2 into products may benefit from the expansion of CO_2 infrastructure and a growing CO_2 market.

Box 8: Preferential procurement of low-carbon concrete

Several governments have enacted policies to source electricity used in government operations (including military) from renewable sources, reflecting shifting commitments and measures to lower carbon emissions. Owing to their size, governments have the ability to sign major power purchase agreements and in some cases, develop sizeable renewable power generation capacities.

Beyond electricity, governments at various levels of jurisdiction are also major consumers of concrete, the production of which can incorporate captured CO_2. Although the momentum seen in renewable power procurement has not yet extended to other products, positive developments are beginning to emerge, with various municipal, subnational and national governments looking at the opportunity to purchase CO_2-based concrete:

- The European Union's LIFE programme, the EU's funding instrument for the environment and climate action, supports the Solid Life project, focused on developing the European market for Solidia Technologies® including CO_2-cured concrete.

- The Government of Ontario (Canada) is looking at how to account for the emissions embedded in cement and concrete in public procurement rules (ECO, 2017).

- The Hawaii Department of Transportation has announced plans to demonstrate the use of concrete made with CO_2-injected concrete on an access road for a major interchange (Carbon Cure, 2019), while the State has also put forward legislation that "requires all state building construction that uses concrete to use post-industrial carbon dioxide mineralized concrete." (Hawaii State Legislature, 2019).

- The New York State Assembly has introduced a bill related to procurement policies requiring the use low embodied carbon concrete for use in state projects (New York State Assembly, 2019).

- The city of Austin, Texas' Environmental Commission has recommended that the city council explore pilot programs using CO_2-based concrete (Austin Monitor, 2019).

To date, several governments and agencies have been supporting innovation surrounding CO_2-conversion technologies. For example, in June 2019 at the G20 Energy Ministers' Meeting, Japan released a Carbon Recycling Roadmap with emphasis on early RD&D for commercialisation of CO_2 use technologies, including goals for commercialisation of polymers and concrete from 2030 and commodity chemicals and fuels requiring hydrogen by 2050 (METI, 2019). Additionally, several prize programmes have been initiated with the aim to promote the development of CO_2 conversion technologies by awarding a prize to the most innovative CO_2 use applications. A notable example is the NRG COSIA Carbon XPrize (Box 9).

Governments can also play a facilitative role by convening stakeholders, particularly industry and academia, and encouraging collaboration through international RD&D programmes. An example is Mission Innovation, which is a coalition of more than 20 countries that pledged to double RD&D funding on clean energy. In 2016, the Mission Innovation countries committed to seven Grand Challenges, including one for CCUS. The programme involves collaboration among experts from many countries in determining RD&D needs (US DOE, 2019).

Box 9: NRG COSIA XPrize: Supporting innovation in CO_2 use

The NRG COSIA Carbon XPrize is a USD 20 million global competition funded by NRG and Canada's Oil Sands Innovation Alliance. Ten finalists from the US, Canada, UK, China and India will be demonstrating their technologies at either the Wyoming Integrated Test Center under the competition's coal track (based at a coal-fired power plant) or the Alberta Carbon Conversion Technology Centre under the competition's natural gas track – with one winner per track to be announced in 2020 (NRG COSIA XPRIZE, 2019).

Applications that are being supported span a wide range of CO_2 use. The ten finalists are:

Coal track	Natural gas track
C4X China — waste-to-chemicals	Carbon Upcycling-NIt Canada/USA — nanoparticles
Breathe Applied Sciences India — Chemicals (methanol)	C_2CNT USA — carbon nanotubes
Carbon Capture Machine Scotland, UK — Chemicals (carbonate feedstocks)	CarbonCure Canada — CO_2-based concrete
CO_2Concrete USA — CO_2-based concrete	CERT Canada — fuels
Dimensional Energy USA — Chemicals	AirCo. Canada — alcohol

Such international competitions are highly valuable to push CCU innovation forward, but should not overshadow the importance of complementary, targeted policy focused on creating markets – specifically to stimulate the demand for, and supply of CO_2-based products.

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