elementenergy

CO_2 UTILISATION OPTIONS FOR REGIONAL DEVELOPMENT

INDUSTRY TRANSITION PLATFORM

A report for

CLIMATE GROUP

The Climate Group

Element Energy

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This report annex has been prepared by Element Energy.

The original report, Fostering Disruptive Innovation, can be found here.

Element Energy is a strategic energy consultancy, specialising in the intelligent analysis of low carbon energy. The team of over 80 specialists provides consultancy services across a wide range of sectors, including the built environment, carbon capture and storage, industrial decarbonisation, smart electricity and gas networks, energy storage, renewable energy systems and low carbon transport. Element Energy provides insights on both technical and strategic issues, believing that the technical and engineering understanding of the real-world challenges support the strategic work.

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Disclaimer

Acronyms

BECCS	Bioenergy with Carbon Capture and Storage
CCS	Carbon Capture and Storage
CCU	Carbon Capture and Utilisation
CCUS	Carbon Capture, Utilisation, and Storage
CfD	Contract-for-Difference
CO_2	Carbon Dioxide
CO_{2e}	Carbon Dioxide Equivalents
CRI	Carbon Recycling International
DME	Dimethyl Ether
ETS	Emissions Trading System
F-T	Fischer-Tropsch
Gt	Giga tonne
ITP	Industry Transition Platform
Mt	Mega tonne
NRW	North Rhine-Westphalia
RD&D	Research, Design and Development
RED	Renewable Energy Directive
TRL	Technology Readiness Level

Contents

1 Introduction

Within the Under2 Coalition, the Industry Transition Platform (ITP) brings together regional governments to develop strategies to reduce industrial emissions while simultaneously ensuring industrial activity maintains its competitive advantage in the long-term. A recent ITP study, Fostering Disruptive Innovation[1], explored key disruptive technologies, policies and business models which regional governments should seek to incorporate into their industrial decarbonisation strategies. As a follow-on to the Fostering Disruptive Innovation study, this annex takes a closer look at one of the disruptive technologies identified: carbon capture and utilisation (CCU).

CCU routes are gathering increasing interest as a means to contribute to industrial emissions reduction and promote circular economy development. In order to achieve deep decarbonisation or net-zero emissions, several industries (e.g. cement, refining) are likely to adopt carbon capture as an abatement technology. For regions which do not have access to CO_2 storage, CCU technologies offer an alternative option for downstream carbon utilisation and management. CCU routes are capable of producing conventional industrial products without the consumption of fossil fuel feedstocks, however each route's CO_2 mitigation potential varies, requiring careful consideration of their net CO_2 emissions abated.

This annex provides insight into the opportunities which exist for CCU to be part of regional industrial decarbonisation plans and strategies. The first chapter presents a high-level overview of CCU and highlights a range of potential pathways. This includes materials, chemicals, fuels and polymers, with a focus on the accelerated mineralisation and catalytic conversion production methods. This overview was based on a review of multiple CCU focused reports that cover a broad range of pathways. The second chapter takes a deep dive into two CCU routes of particular interest to the ITP regional governments: CO_2 to methanol and CO_2 cured concrete. The final chapter covers the role regional governments can play in identifying opportunities and connecting organisations, facilitating RD&D and introducing policy support mechanisms.

2 Summary of CCU Technologies

The conversion of CO_2 to value-added products can occur through a variety of different chemical conversion pathways. Two dominant pathways identified by number of developers, number of projects, and technology readiness levels (TRL[2]) are thermo-catalytic conversion and accelerated mineralisation (see Figure 2). These routes have the largest number of technology developers and include developers that have reached advanced stages of development (TRL 7-9)[3]. Other routes that may hold future potential are currently either at lower stages of development or have lower levels of developer interest. These include fermentation and photosynthetic routes, which have low numbers of developers but have reached pilot system demonstrations (TRL 6-7), as well as electrochemical and photocatalytic routes, which have higher numbers of developers but are mostly at laboratory testing stages (TRL 4-5)[3].

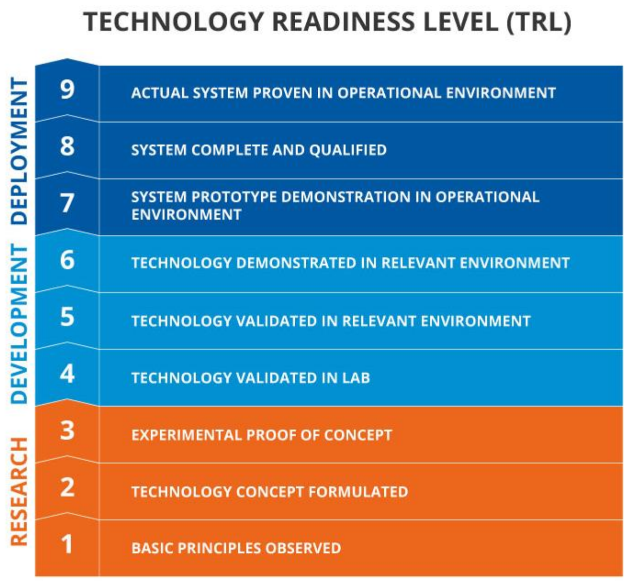

Figure 1: Technology readiness levels broken down by research, development, and deployment phases

[1] Element Energy, Fostering Disruptive Innovation – Industry Transition Platform (2020). [LINK]
[2] As shown in Figure 1, technology readiness level (TRL) defines the technical maturity of a technology throughout its development lifecycle. Source for Figure 1: [LINK].
[3]Lux Research 2016, Global Roadmap Study of CO2U Technologies (distributed by Global CO_2 Initiative) [LINK]

This annex focuses on accelerated mineralisation and catalytic conversion pathways for CO_2 utilisation. These can be used to produce a wide variety of products including building materials, fuels, chemicals, and polymers using CO_2 as a feedstock. Within these pathways, distinctions can be made between the types of feedstock that are needed alongside CO_2 for the conversion process. For accelerated mineralisation pathways, most routes react CO_2 either with alternative cements or with alkaline waste residues. For catalytic conversion pathways, dominant routes either react CO_2 with hydrogen or with higher value chemicals, such as alcohols or epoxides. Notable characteristics of these pathways are outlined in Figure 2 with further discussion below.

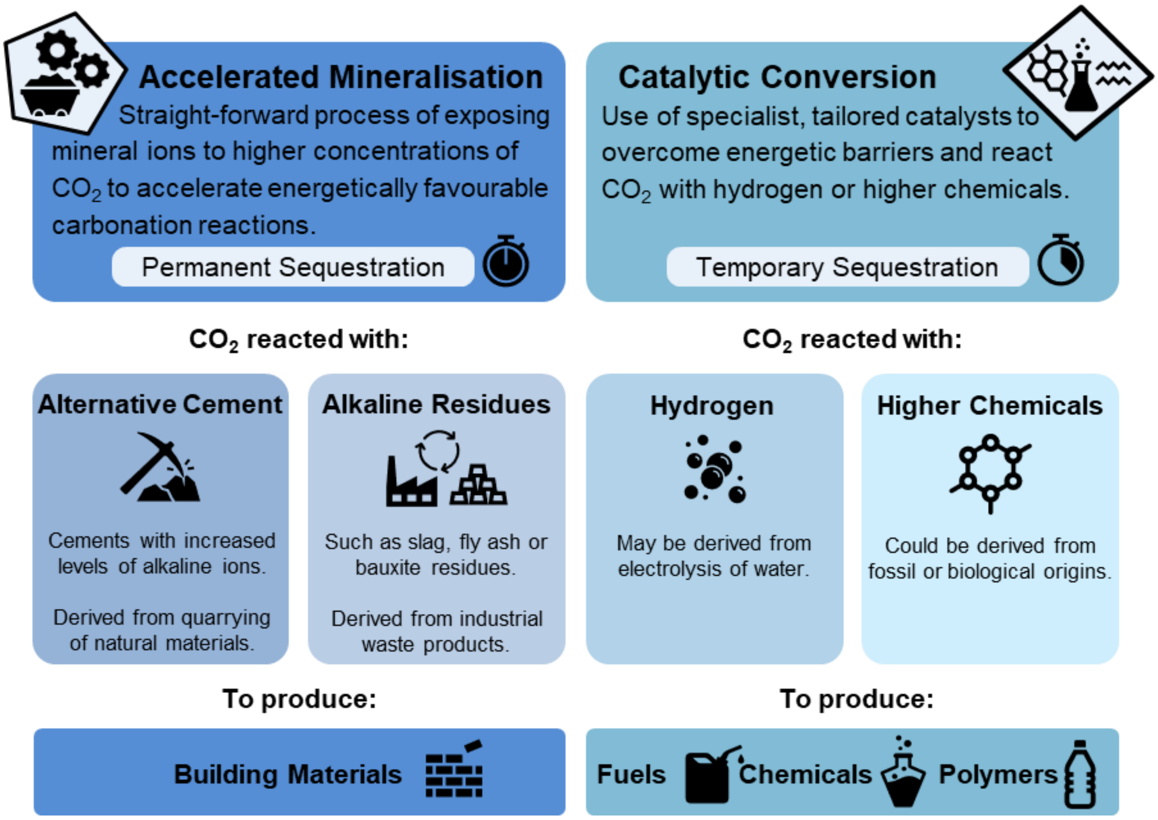

Figure 2: Characteristics of the accelerated mineralisation and catalytic conversion pathways

2.1 CO_2 mineralisation using alternative cement

Cement is a powder-like substance derived from quarried materials such as limestone and clay. It is typically mixed with water to create a paste that slowly hardens ('cures'), binding together other materials that it is mixed with (such as sand and gravel) to make building materials, such as concrete. This process can be altered to incorporate CO_2 utilisation during the curing stage, with CO_2 being permanently stored as a mineral carbonate within the binder. One approach that can be used to make pre-cast concrete products (such as concrete blocks, slabs, and pipes) involves the use of an alternative cement and a curing chamber with an increased CO_2 atmosphere. The cement cures through reacting with CO_2 rather than water. This route is being brought to market by the US based company Solidia Technologies[4] who use a special cement high in calcium silicate minerals. Their technology has been tested by several pre-cast customers in North America and Europe. Other approaches in advanced development include the injection of CO_2 during concrete mixing using normal cement, and the replacement of cement with a steel slag-based binder. The former has been commercialised by CarbonCure[5] (Canada), with a focus on its ability to reduce cement consumption. The latter is being explored by a few developers including Carbicrete[6] (Canada) and Carbstone Innovation[7] (Belgium).

[4] Solidia Technologies online 'Information Kit' [LINK] [accessed April 2021] including Science Backgrounder [LINK]
[5] CarbonCure 2017, Calculating sustainability impacts of CarbonCure ready mix [LINK]
[6] CarbiCrete website [LINK]
[7] Technology developed by ORBIX with VITO - ORBIX website [LINK] [accessed April 2021]

2.2 CO_2 mineralisation using alkaline waste residues

Around 2 Gt of alkaline waste residues are produced globally each year, from industries including steel production (slag), alumina extraction (bauxite residues), cement production (cement kiln dust), and coal-fired power generation (fly ash)[8]. This CO_2 utilisation route uses accelerated carbonation as a treatment to stabilise these residues, allowing their potential re-use in applications such as aggregates in the construction industry. The CO_2 reacts with ions (such as Ca^{2+} and Mg^{2+}) in the residue to form stable mineral carbonates, permanently sequestering the CO_2 and acting to inhibit the leaching of these ions into the environment. This allows the wastes to be safely re-purposed, avoiding alternative treatments and landfill or waste-pile disposal.

The utilisation process can be straight-forward, involving exposing waste residues to higher concentrations of CO_2 to accelerate natural carbonation reactions. The route has been used commercially in the UK since 2012, with three facilities converting air-pollution control residues into aggregates for use in concrete blocks[9]. One developer that has reached market introduction (TRL 9) of their technology is Carbon8 Systems (UK). The company has developed a containerised unit that can be installed at a site where waste residues are produced and utilise CO_2 from flue gases at the site[10]. The system then converts the wastes and CO_2 into a lightweight aggregate product. This technology is being commercially deployed at a VICAT cement plant in France, where it will convert cement bypass dust to aggregate[11]. Other technology developers are at advanced stages of technology demonstration for the mineralisation of steel slag, including Carbicrete[6] (Canada) and Carbstone Innovation[7] (Belgium).

2.3 Catalytic reaction of CO_2 with hydrogen

The catalytic reaction of CO_2 with hydrogen can be used to produce a variety of simple chemicals, such as methanol or methane, as well as fuels such as hydrocarbons or dimethyl ether. These routes may directly react hydrogen and CO_2 or they may go via an intermediate step of syngas creation, as shown in Figure 3. Both methods involve the use of specialised, tailored catalysts to guide the reaction and overcome energetic barriers. The requirement for hydrogen as a feedstock for this utilisation process makes it energy intensive. This hydrogen is often expected to come from electrolysis of water using a very low-emission electricity source, such as renewable wind or solar power.

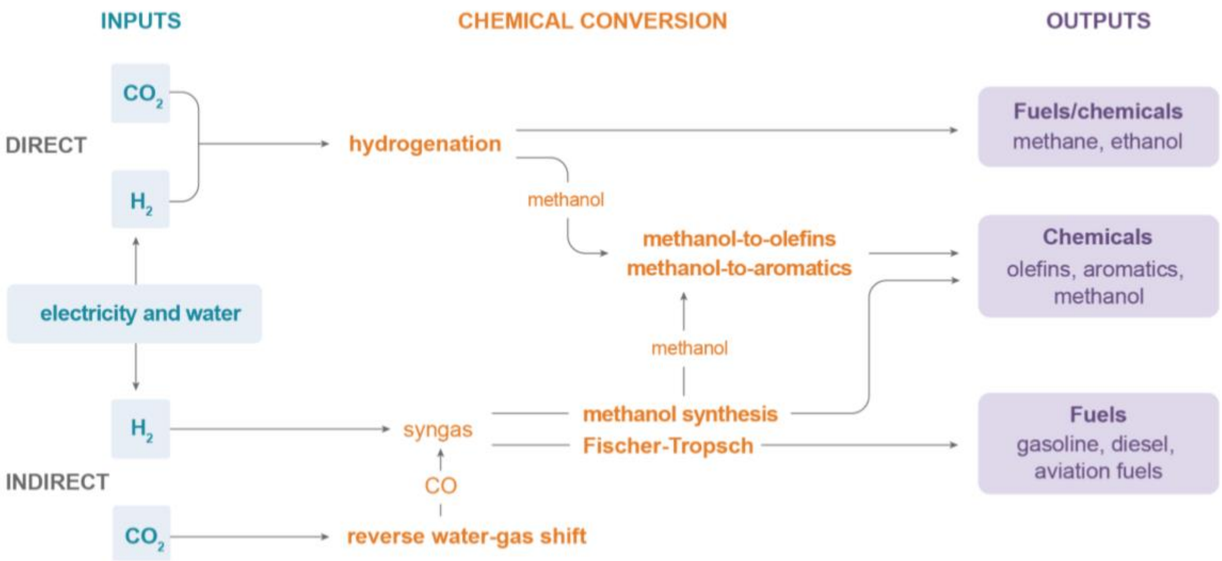

Figure 3: Catalytic conversion pathways for CO_2 with hydrogen (IEA 2019) [12]

[8] Gnomes et al. 2015, Alkaline residues and the environment [LINK]
[9] OCO Technology, previously Carbon8 Aggregates, website [LINK]
[10] Carbon8 Systems website [LINK]
[11] Carbon8 Systems 2020, Press Release: Carbon8 Systems to deploy its pioneering technology at Vicat Group cement company in France [LINK]
[12] IEA 2019, Putting CO_2 To Use [LINK] [image taken directly]

There are many different CCU routes in this category with varying stages of technology development, ranging from lab-based research on catalyst designs to industrial demonstrations and planned large-scale deployments. A selection of products from more advanced routes and their developers are presented below

CO_2 to Methane: Methane, or synthetic natural gas, is used across industries as a fuel for heating, power, and transport. There have been almost 70 demonstration projects for CO_2 conversion to methane, mostly located in European countries and in Germany in particular[13]. A developer in advanced stages of technology development for the catalytic hydrogenation route is ETOGAS (Germany). Their technology was deployed in 2013 in an industrial plant producing methane ('e-gas') on behalf of Audi AG in Werlte, Germany[14].

CO_2 to Methanol: Methanol is used as a building block for many higher value chemicals and fuel additives. It can also be used as a feedstock for olefins (used to make plastics) and gasoline. Technology for conversion of CO_2 to methanol has reached the stage of market introduction, having been commercialised by Carbon Recycling International (CRI). Since 2012, the company has operated the George Olah Renewable Methanol plant in Iceland producing its 'Vulcanol' branded product sold to customers in Europe and China[15].

CO_2 to Hydrocarbons: CO_2 can be converted to carbon monoxide and combined with hydrogen to give syngas (CO + H_2). This syngas can then be converted, using established Fischer-Tropsch (F-T) synthesis, to a synthetic crude oil which is then refined to give a range of hydrocarbon fuels, such as diesel, gasoline, or jet fuel. A developer that has demonstrated this technology in a pilot system (TRL 7) is Sunfire (Germany)[14]. There is particular interest in the route for making sustainable aviation fuel. An industrial-scale deployment of the technology being planned, under the project 'Norsk e-fuel', would see an operational facility in Norway by 2023[16].

2.4 Catalytic reaction of CO_2 with higher chemicals

Some routes were identified in which captured CO_2 was reacted with more complex chemicals, such as alcohols or epoxides, that may have been fossil derived[14]. These included processes to incorporate CO_2 as a carbonyl (C=O) group in chemicals and polymers, acting as a partial substitute for a fossil-based feedstock. There are a number of operational polymer plants that use CO_2 as a raw material. One route of recent interest is the copolymerisation of CO_2 with epoxides to produce polyols. Polyols can be used to make flexible and rigid foams that have a wide variety of end-uses, such as in mattresses, furniture upholstery, and vehicle interiors[14]. Developers in this area include Covestro (Germany), Novomer (US), and Econic (UK)[14]. The technology has reached the stage of market introduction (TRL 9) with products being trialled for new applications[14]. CO_2 is incorporated into polymer backbones as a partial substitute for fossil-derived epoxide feedstocks. The CO_2 content can be tuned for different material properties up to 50% by weight[17].

[13] Theme at al. 2019, Power-to-Gas: Electrolysis and methanation status review [LINK]
[14] IEA Clean Coal Centre 2019, Developments on CO_2-utilization technologies [LINK]
[15] Carbon Recycling International website [accessed Feb 2021] – George Olah Renewable Methanol [LINK] and Vulcanol [LINK]
[16] Norsk e-Fuel 2020, Press Release: Norsk e-Fuel is planning Europe's first commercial plant for hydrogen-based renewable aviation fuel in Norway [LINK]
[17] ECOFYS 2017, Assessing The Potential Of CO_2 Utilisation In The UK. [LINK]

2.5 CCU products and characteristics

A non-comprehensive selection of products produced using mineralisation or catalytic conversion CCU pathways are shown in Table 1, with details on applications and potential impacts. From a review of the literature, it was found that there were often similarities between products made using a similar type of utilisation pathway in terms of factors impacting costs, mitigation of emissions, and co-benefits or trade-offs. Some overarching drivers, barriers and enabling factors were also identified. These are discussed in the following sub-sections.

Table 1 Non-comprehensive list of CCU products and their applications/impacts

Product	Utilisation Pathway	Applications	Impact
Pre-cast concrete	Mineralisation of alternative cement or waste residues	Concrete blocks, slabs, pipes	Permanent sequestration. Avoids cement emissions. Reduced quarrying. Waste treatment & reuse.
Aggregates	Mineralisation of waste residues	Lightweight aggregate for use in concrete blocks	Permanent sequestration. Reduced quarrying. Waste treatment & reuse.
Methanol	Catalytic reaction with hydrogen	Solvent, chemical intermediate, gasoline blending, M100 fuel, methanol-to-olefins	Avoids fossil-derived methanol. Use of CO_2 offsets end-of-life emissions. High energy consumption.
Dimethyl Ether (DME)	Catalytic reaction with hydrogen	Alternative fuel (diesel replacement)	Avoids fossil-derived DME. Cleaner alternative to diesel fuel. High energy consumption.
Hydrocarbons (synthetic crude)	Catalytic reaction with hydrogen	Drop-in fuels: diesel, gasoline, jet fuel	Avoids crude oil extraction. Use of CO_2 partially offsets combustion emissions. High energy consumption.
Methane (synthetic natural gas)	Catalytic reaction with hydrogen	Drop-in natural gas: heating, cooking, fuels	Avoids natural gas extraction. Use of CO_2 partially offsets combustion emissions. High energy consumption.
Polyols (polyether carbonates)	Catalytic reaction with higher chemicals (epoxides)	Flexible & rigid foams (upholstery, mattresses) Coatings & adhesives	CO_2 partially replaces fossil-derived epoxides in the polyol. Reducing fossil consumption.
Polycarbonates	Catalytic reaction with higher chemicals (alcohols or epoxides)	Hard plastics with a variety of applications	Temporary sequestration of CO_2.

Cost & Market Competitiveness

A recent scoping review of academic literature[18] found that pathways to produce fuels and chemicals using CO_2 utilisation were more expensive than current prices of incumbents, and for hydrocarbons and methane especially this is expected to remain the case in the long-term. However, pathways producing building materials and polymers could have comparable or lower costs today. Table 2 shows median cost estimates for select CCU products compared to present day prices, as reported by the study.

Table 2 Cost estimates for a selection of CCU products and product groups[19]

Pathway	Cost of product made with CO_2 utilisation (US$ per tonne of product)	Selling price of product (US$ per tonne of product)	Difference (%)	Cost premium of CO_2 Utilisation (US$ / t CO_2 utilised)
Polymers	1,440	2,040	-30%	**Chemicals:** -$80 to $320
Methanol	510	400	+30%	
Methane	1,740	360	+380%	**Fuels:** $0 to $670
F-T fuels	4,160	1,200	+250%	
Dimethyl ether	2,740	660	+320%	
Aggregates	21	18	+20%	**Building Materials:** -$30 to $70
Cement curing	56	71	-20%	

The high costs of chemicals and fuels is linked to the high energy requirements to produce hydrogen for these pathways, as well as the low level of development of some routes giving low yields and high catalyst costs. As hydrogen prices can dominate costs, the availability of low-cost renewable electricity for electrolysis is essential for lowering the costs of these routes. One opportunity is to make use of surplus renewable electricity that would otherwise be curtailed. In the fuels sector, a cost premium could be acceptable provided the benefits of CCU fuels are recognized within existing political and regulatory incentives. In comparison, there are currently limited drivers in the chemicals market to justify the cost premium for CCU products.

The cost-competitiveness of building materials and polymer routes are dependent upon the relative cost of the counterfactual feedstock and the cost of CO_2 supply. For building material routes, cost savings could be achieved through lowering cement costs or from the avoidance of gate fees for waste disposal. Some concrete routes also claim that the CCU product has enhanced properties, which could therefore potentially justify a cost premium. For the polymer routes, cost-savings may be achieved if the CO_2 replaces expensive feedstocks (such as epoxides in the case of polyols) or potentially due to the CCU reactions having lower waste products with less need for subsequent separation or purification steps.

Mitigation of Emissions

Emission mitigation can be due to permanent sequestration of captured CO_2 (mineralization pathways) and/or due to the avoidance of emissions from a counterfactual product (mineralization & catalytic pathways). For catalytic pathways, emission mitigation depends highly on the emissions associated with producing the non-CO_2 reactant, especially for routes using hydrogen. For example, routes could have greater emissions than the counterfactual if non-renewable electricity is used for electrolysis. To fully understand the mitigation

[18] Nature 2019, The technological and economic prospects for CO2 utilization and removal [LINK]
[19] Adapted from: Nature 2019, The technological and economic prospects for CO2 utilization and removal [LINK] – cost premium refers to the breakeven cost of CO_2 utilisation adjusted for revenues, by-products, and any CO_2 credits or fees. Values were estimated in the study based on a scoping literature review, with median values shown for CCU product costs and an interquartile range shown for cost premium.

potential of CCU pathways a lifecycle assessment is needed, however these also contain challenges and are not always comparable. The accounting of captured CO_2 is also an important consideration.

Figure 4 indicates the relative climate benefits of CCU product groups per tonne of CO_2 used (y-axis) alongside the maximum global potential for CO_2 utilisation (x-axis), as reported by the International Energy Agency.

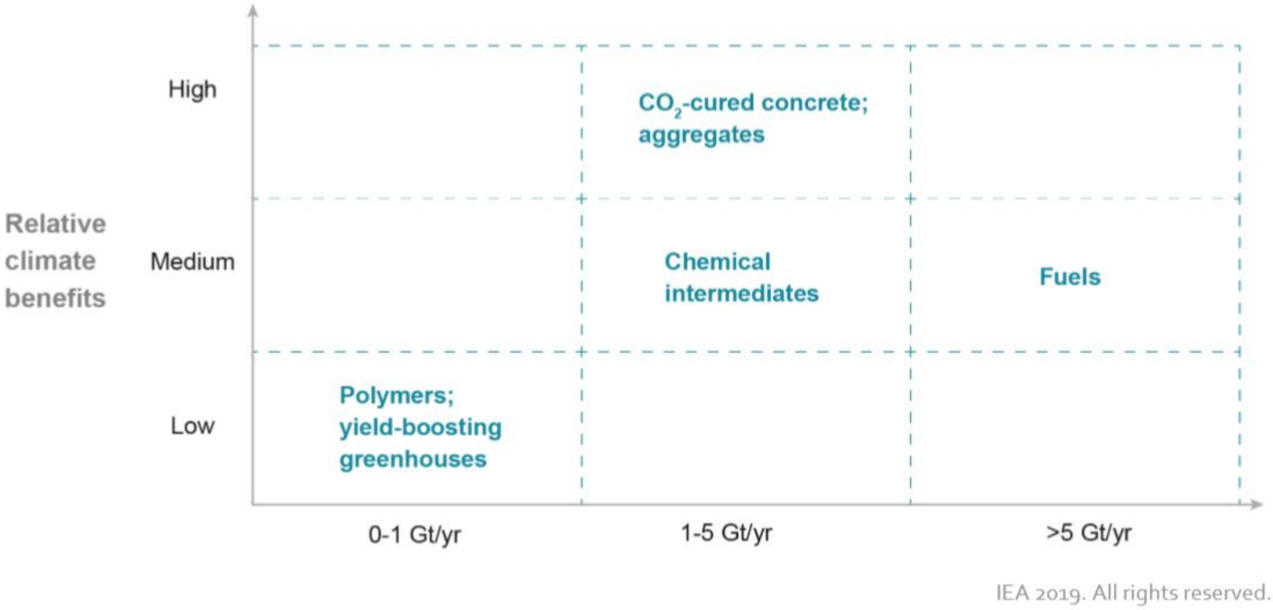

Figure 4: Relative climate benefits against maximum global CO_2 utilisation potential (IEA, 2019)[20]

Co-Benefits & Trade-Offs

Several additional co-benefits associated with the above CCU conversion pathways were identified and are included as a summary below:

Accelerated Mineralisation	Catalytic Conversion
• Treatment & re-use of waste residues • Avoidance of landfill & disposal fees • Avoidance of quarrying new material	• Lower fossil resource consumption • Cleaner burning fuels • Safer chemical routes • Continued use of existing assets • Energy storage applications / Power to X

In addition, an identified trade-off for the catalytic conversion routes using hydrogen was the large renewable energy requirements for water electrolysis. This is also associated with large land-use requirements for renewables deployment.

[20] IEA 2019, Putting CO_2 To Use [LINK] [image taken directly] - X-axis shows theoretical maximum global potential for CO_2 use (Gt CO_2 utilised per year) if all conventionally produced products were replaced with the CCU route. Y-axis shows IEA estimate of relative climate benefit per tonne of CO_2 utilised.

2.6 What regions might CCU be relevant for?

High availability of low-cost renewables	• Regions with very low-cost renewables could be optimal locations for CCU, allowing fuel and chemical products to be more cost-competitive • CCU could prevent curtailment of renewables, acting as a grid-balancing or energy storage option by converting surplus electricity to fuels
Planning a hydrogen economy	• CCU could help scale-up hydrogen supply chains by providing an assured but flexible demand • CCU can convert hydrogen to an alternative energy carrier (such as methane or hydrocarbons) that could use existing distribution networks
Limited CO_2 storage options or acceptance	• CCU could provide a destination for captured CO_2 when geological storage options are not available • CCU facilities could be located near to emitters (such as in industrial clusters) lowering the need for CO_2 transport & storage • CCU may be more socially acceptable than CCS in some regions
Existing industry & work force	• Some CCU routes use similar equipment or processes to existing production practices, making regions with existing skills optimal locations • CCU could allow for continued use of existing assets (such as F-T fuel refineries) and labour force retention as industry transitions to net-zero • Relevant industries include chemicals/polymers, cement/aggregate, and industries producing alkaline waste such as metal extraction/processing
Innovation ambitions	• The novelty of many CCU routes provides an opportunity for regions to lead the way in innovation and development • Regions could become world leaders or pioneers for specific new technologies, developing early manufacturing capabilities & expertise
Circular economy principles	• By re-using CO_2 as a feedstock, CCU can lower-consumption of limited resources, such as fossil reserves in the case of chemicals and fuels or quarried/mined raw materials in the case of building products • CCU involving carbonisation of waste products can allow for these wastes to be repurposed, preventing their disposal in land-fill • In some cases, CCU routes could lower the production of waste products

3 Technology Deep Dives

During the initial literature review, five pathways were identified as potential options for further investigation based on the level of development, availability of information, mitigation potential, and applicability to regional governments. These pathways were:

- CO_2 Cured Concrete
- Waste-to-Building Materials
- CO_2 to Methanol
- CO_2 to Fischer-Tropsch Fuels (diesel, gasoline, jet fuel)
- CO_2 to Polyols

The preliminary research on each of these pathways is included in the Appendix. Two of these were selected for technology deep-dives - 'CO_2 to Methanol' and 'CO_2 Cured Concrete' - and are discussed in more detail within this chapter.

3.1 CO_2 to Methanol

Methanol can in theory be produced from CO_2 using a range of different conversion routes, such as catalytic hydrogenation, photocatalytic conversion, and electrochemical conversion. These routes all produce an identical methanol product. This deep-dive focuses on catalytic hydrogenation technology, as this has been demonstrated at pilot scale and is well studied in the literature.

Technology Overview

The conversion of CO_2 to methanol involves catalytic reaction of CO_2 with hydrogen, using a new chemical plant rather than retrofits of existing plants. Production of 1 tonne of methanol uses 0.2 tonnes of hydrogen and 1.46 tonnes of CO_2[21]. The conversion route is well-studied in academic literature, with the typical assumption that hydrogen is produced from water electrolysis. Therefore, it requires significant renewable electricity provision; however, this could be supplied intermittently.

The lead developers for CO_2 to methanol are Carbon Recycling International[22]. We would describe their technology to be TRL 7-8 in 2021. The full system has been incorporated into an operational 4 kt plant in Iceland since 2012, qualifying its performance under relevant industrial conditions. There are additional smaller scale pilot plants in Sweden and Germany demonstrating the technologies' ability to use different CO_2 sources and an intermittent power supply. Plans for commercial scale plants in China and Norway[23] are currently being developed. It is therefore expected that the technology will exceed TRL 9 within the next 5 years.

Emission Mitigation

The CO_2-to-methanol route allows avoidance of emissions but does not provide negative emissions nor permanent CO_2 sequestration. Fuels, chemicals, and polymers made from methanol have short lifetimes (from a few days to a few decades) with the CO_2 released to the atmosphere at end-of-life. The avoidance is due to this CO_2 having been re-used rather than emitted immediately, and the displacement of the conventional fossil-based methanol production pathway. Assuming 100% conversion, the route requires 1.37 tCO_2 per tonne of methanol. The total reduction in lifecycle emissions compared to a counterfactual has been reported as 0.5-1 tonne of CO_2eq per tonne of methanol, equating to a 74% to 93% reduction[24]. Based on this estimate, 0.4-0.7 tCO_2eq can therefore be avoided for every tonne of CO_2 utilised. However, these values are an optimistic example, with actual impacts highly dependent on plant specific parameters, the counterfactual choice, and the emission intensity of the energy used.

[21] Perez-Fortes et al. 2015, Methanol synthesis using captured CO_2 as raw material [LINK]
[22] Carbon Recycling International projects are listed on their website with further information [LINK]
[23] Stratkraft 2020, Press Release: Industrial partners to develop first of its kind eMethanol plant in Norway [LINK]
[24] IEA 2019, Putting CO_2 To Use [LINK]

Interest & Applications

Methanol has applications both as a chemical feedstock and as a liquid fuel, with dominant end-uses including processing to formaldehyde, conversion to olefins (used in plastics), and gasoline blending. Global production of methanol was around 100 Mt in 2020, of which 20% went to fuels[25]. Currently methanol blending in motor gasoline is restricted by fuel quality standards to 3% by volume in Europe and 5% in the United States, however higher blends are used extensively in China[26]. Interest in the production of methanol from CO_2 is linked to the cleaner production pathway (avoiding natural gas), the opportunity to reuse CO_2 emissions, and the potential to use renewable electricity that would otherwise be curtailed. Future end-uses of CCU methanol may be in applications that are difficult to decarbonise, such as chemicals, polymers, and select fuel applications such as marine fuels or heavy-duty road transport. At each stage of conversion (electricity to hydrogen to methanol) there are energy losses, so the use of electricity or hydrogen directly, if possible, is likely more efficient than use of methanol from CO_2[24].

Costs & Optimal Siting

It is estimated that producing methanol from CO_2 costs at least twice[21] that of conventional production routes, which derive methanol from either natural gas or coal feedstocks. However, this cost could be comparable to bio-methanol routes, and cost competitiveness will depend on local market prices[24]. The dominant cost component is that of hydrogen production from electrolysis, with the potential for cost reductions linked to the evolution of emerging electrolyser technologies or the use of very cheap renewable electricity. Optimal siting of a CO_2-to-methanol plant would therefore be in an area with low-cost or surplus renewable electricity. The route also requires a high purity CO_2 feedstock. The current largest CO_2-to-methanol facility is the George Olah Renewable Methanol plant in Iceland, where there is vast availability of renewable electricity from hydropower and geothermal sources. The facility accesses high purity CO_2 from a nearby geothermal power plant. There are also plans to build a large-scale CO_2-to-methanol plant in Norway, leveraging the regions abundant supply of renewable electricity and CO_2 from a co-located ferrosilicon plant[23].

Existing & Future Support

The cost premium of methanol from CO_2 means that political or regulatory support is needed to either improve product cost-competitiveness or to increase demand through enabling a price premium. A relevant support mechanism is the use of mandates such as sustainable fuel obligations, with the EU Renewable Energy Directive (RED II) and the California Low Carbon Fuel Standard being notable examples. RED II requires 14% of energy consumed for road and rail transport to be of renewable origin by 2030, with CO_2-derived fuels included in this target under specific conditions, and limits placed on the contribution allowed from biofuels[27]. The California Low Carbon Fuel Standard sets declining allowances for the lifecycle carbon intensity of fuels supplied in the state, with costs incurred for exceeding these allowances. These mechanisms create a market for sustainable fuels, and therefore could support the uptake of CO_2-to-methanol for gasoline blending or alternative fuels.

Existing CO_2-to-methanol projects have been enabled through funding grants, private investments, and company partnerships. The market leading developer, Carbon Recycling International (CRI), has so-far received funding under the EU Horizon 2020 programme for 4 pilot projects aimed at demonstrating specific potential applications[22]. The planned facility in Norway is a partnership between CRI, Statkraft (renewable energy provider), and Finnfjord (providing CO_2). Activities that may further enable the market uptake of CO_2-to-methanol in fuel applications could be the local trialling of methanol vehicles (road and marine) or engaging engine manufacturers in trials to use higher methanol blends (vehicle compatibility and engine testing).

[25] Using 2020 data from the MMSA via the Methanol Institute, 25%, 26% and 13% of global methanol demand was for formaldehyde, olefins, and gasoline blending respectively. [LINK]
[26] IEA AMF webpage on Fuel Information: Methanol [LINK] [accessed Jan 2021]
[27] EU science hub webpage: Renewable Energy – Recast to 2030 (RED II) [LINK]

3.2 CO_2 Cured Concrete

Several different routes for the use of CO_2 in the curing of concrete are in advanced stages of development. This deep-dive focuses on the use of alternative cement (non-waste derived). Justification for this is that the route offers greater utilisation of CO_2 compared to conventional cement routes and it is seen to have wider regional applicability than waste routes, as it does not rely on waste availability or end-of-waste regulations.

Technology Overview

The investigated route involves the production of concrete using an alternative cement (high in calcium silicate minerals) and the exposure of this concrete to higher than atmospheric concentrations of CO_2. The CO_2 reacts with the minerals in the cement to form stable mineral carbonates, and this process hardens ('cures') the concrete mixture. The composition of concrete products is variable but typically it might consist of up to 15% cement by weight, with aggregate (crushed rock, gravel, sand) making up the remainder. The process then utilises approximately 0.3 tCO_2 per tonne of cement[28].

A developer in advanced stages of development is Solidia Technologies[29]. We would describe their technology to be TRL 7 in 2021, meaning the technology has been demonstrated in an integrated pilot system within a relevant environment with the system design virtually complete. Industrial scale pilot projects are ongoing in Canada, Germany, France, and UK with further projects planned. It is expected that further developments will need to demonstrate long-term durability of the products and scale-up production.

Emission Mitigation

The CO_2 cured concrete route considered here allows both permanent sequestration of utilised CO_2 as well as additional emissions avoidance. Utilised CO_2 is sequestered as a stable mineral carbonate in the concrete, with the potential to sequester up to 300 kg of CO_2 per tonne of alternative cement used, with actual values of 230 kg CO_2 having been measured[28]. Production of the alternative cement is reportedly up to 30% less emission intensive than conventional Portland cement production, leading to avoided emissions of approximately 250 kg CO_2 per tonne of cement used[28]. This results from the use of lower temperatures and a reduction in limestone consumption, which respectively reduce emissions from fuel combustion and calcination. These factors combined could allow for up to a 70% reduction in the carbon footprint of cement production and use[28]. This is significant as cement production emissions are notably difficult to abate, and cement dominates the emission intensity of concrete. As an indication, if a concrete product is composed of 15% cement by weight, a mitigation potential of 80 kg CO_2 per tonne of concrete could be realised.

Applications & Siting Factors

Concrete, which is composed of cement and aggregate, is one of the most widely manufactured construction materials with global production estimated at 30 Gt in 2019, using approximately 4 Gt of cement[30]. The CCU application considered here of concrete curing using CO_2 and alternative cements is relevant to the pre-cast segment of this market due to the need to use a CO_2-curing chamber. This segment is a relatively small proportion of the total concrete market, covering prefabricated products such as blocks, tiles, sleepers, and pipes. Typically building material products such as concrete are localised markets. The curing technology can be sited at existing pre-cast concrete sites, using very similar processes to existing production routes[29]. Equally production of the alternative high calcium silicate cement can be achieved through modification of existing cement production routes[29].

Interests & Cost

Alongside the potential to permanently sequester CO_2, drivers for the development of CO_2-cured concrete include opportunities to improve the manufacturing process, such as reducing curing times, lowering energy use for cement production, and lowering water consumption. It is thought that the CO_2-cured route could be

[28] DeCristofaro et al. 2017, Environmental Impact of Carbonated Calcium Silicate Cement-Based Concrete [LINK]
[29] Solidia Technologies online 'Information Kit' [LINK] [accessed April 2021]
[30] IEA 2019, Putting CO_2 to Use [LINK]

cost-competitive with conventional production, for example if cost-savings from cement and curing times outweigh the additional cost of CO_2 supply. There are however several barriers to market adoption. The construction industry is historically conservative, with slow rates of adoption for novel materials and the need for products to have demonstrated their performance over long-term trials[30]. In addition, the construction industry is governed by an extensive set of standards and codes which can vary by region and may need updating to accommodate the use of alternative cement[30]. Early applications for CO_2 cured concrete may therefore be in non-structural applications – such as roads, floors, and ditches – where performance requirements are less stringent[30].

Existing & Future Support

The CO_2 curing route considered here is in advanced stages of development, with multiple pilot demonstrations and products being commercialised in the US and Western Europe. This progress has been enabled through funding support, private investments, and company partnerships. A notable partnership is that of Solidia Technologies, a US based developer of alternative CO_2 cured cements, and Lafarge Holcim, a dominant global player in the cement industry. The companies have together conducted several industrial scale pilots for both the production of an alternative calcium silicate cement and the production of CO_2 cured concrete, using sites in the US, UK, France, Germany, and Canada[31,32]. European pilots received partial funding from the EU's LIFE programme[33], whilst initial RD&D received funding under the US Department of Energy's National Energy Technology Laboratory.

A potential mechanism that could drive uptake of lower emission or more sustainable building materials, such as CO_2 cured concrete, is the use of green public procurement rules or guidelines[34]. This acts to provide an assured demand for low-carbon products through leveraging government purchase power. Such measures could also be implemented at the regional level or by private companies using internal procurement guidelines. These could be implemented by setting minimum standards for the environmental rating of new projects, for example the use of BREEAM ratings in the UK or the IS rating scheme in Australia. Alternatively, emission reduction ambitions could be considered in tender evaluation, such as the Netherlands CO_2 Performance Ladder certification scheme. To benefit CCU concrete, consideration of the embodied emissions of building materials needs to be included, for example through lifecycle assessment.

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[31] LafargeHolcim 2020, Press Release: LafargeHolcim ramps up partnership to capture CO2 in building materials [LINK]
[32] Further details on pilot projects can be found on the Solid Life Project website [LINK] including the International VDZ Congress 2018 presentation [LINK]
[33] Results from EU Solid Life project summarised here: [LINK]
[34] Kadefors et al, Designing and implementing procurement requirements for carbon reduction in infrastructure construction – international overview and experiences [LINK]

4 Recommendations and Next Steps

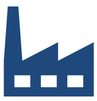
The following sections consider the gaps and barriers for enabling CCU technology development, developing product demand, achieving cost-competitiveness, and driving large-scale deployment. A summary of actions and policy recommendations are provided in each section, concluding with a discussion on the key options which can be undertaken at the regional level.

4.1 Enabling technology development & demonstrating product suitability

CCU technologies are at various stages of development with some routes nearing or already achieving commercial scale deployment. However, many are nascent technologies which require further RD&D to optimise processes to achieve lower costs and lower energy demands. Routes such as those for synthetic fuel production will need to achieve greater scales of demonstration in order to gain investor confidence in supporting new projects. Moreover, given the highly conservative nature of some existing markets, demonstration projects may require many years of operation.

In addition, products themselves are also subject to meeting existing standards and regulations, some of which may be set by regional governments (e.g. fuel standards). These may involve lengthy and expensive processes which hinder CCU technology from receiving development approval. To enable CCU technology development and the demonstration of product suitability, Table 3 below highlights key supporting policies/actions.

Table 3 Policies and actions to enable technology development and demonstrate product suitability

 Stakeholder engagement	• Support cross-disciplinary research in relevant areas • Facilitate engagement between standards agencies and industry to update standards to be performance based[35] • Encourage and facilitate partnerships, collaborations, and private investment between relevant players
 Innovation and demonstration projects	• Provision of funding (e.g. innovation grants) • Facilitate site planning and permitting to streamline demonstration projects and project feasibility studies • Raise awareness to aid societal readiness and acceptance • Support associated infrastructure (i.e. hydrogen or CO_2 transport)
 Product testing and approvals processes	• Share knowledge and support collaboration between industrial actors to streamline approval processes • Trial local projects to encourage regional uptake and investment • Work with over-arching agencies involved in material specifications (e.g. building/fuel standards) to facilitate regulatory approvals

4.2 Developing market interest and product demand

Another key challenge for the CCU routes explored in this study are that market drivers are typically insufficient to justify cost premiums for CCU products. Currently, procurers often lack awareness or engagement with their Scope 3 emissions (e.g. supply chain emissions embedded in chemicals purchased by consumer product manufacturers). This then leads to a lack of awareness around the benefits that CCU products bring, particularly around the benefits which can be realised in the future through robust carbon accounting practices. Consumer perception could drive demand for low carbon goods produced from CCU routes, however, societal

[35] Standards that require a product to meet a certain set of performance requirements, based on needs for the application (e.g. strength/durability standards for concrete).

readiness may be a barrier to developing new markets if misconceptions and concerns are not managed. To drive further demand for CCU products, Table 4 outlines supportive actions and policies that could be used.

Table 4 Policies and actions to develop CCU product demand and market growth

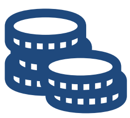
 Lifecycle and Scope 3 emissions	• Facilitate knowledge sharing between industries and investors to aid monitoring and engagement with Scope 3 emissions • Develop emission reporting obligations or guidelines • Develop certification schemes and product labelling or rating systems • Clarify carbon accounting processes for CCU products (e.g. life cycle assessments) and support their alignment with international methods
 Societal readiness and consumer perception	• Raise consumer awareness of lifecycle emissions, circular carbon principles and potential benefits of CCU (linked to product labelling) • Work to dispel misconceptions through engagement to understand consumer/user concerns
 Mandates or standards for low emission products	• Establish local green public procurement guidelines or evaluation systems, ensuring these are performance based rather than prescriptive • Develop voluntary procurement guidelines for industry or encourage industry to collaborate / develop their own green procurement strategies • Introduce product mandates or standards (could be linked to planning permissions or taxes)

4.3 Achieving market cost-competitiveness

While the above supporting actions can help to increase market growth and awareness, CCU products still struggle to achieve comparable levels of cost-competitiveness with incumbent production routes. Certain commodities can be significantly more expensive than conventional fossil-based products which may also be in receipt of subsidies.

However, a select few routes are driven by cost-savings or improving the values of products (e.g. building materials/polymers). In addition, avoidance of fees or compliance with regulations could become a driver if more ambitious incentives or targets are imposed (e.g. avoidance of increasing carbon prices by selecting CCU routes with high mitigation potential). To aid in achieving market cost-competitiveness across various CCU routes, Table 5 outlines the key supporting actions and policies.

Table 5 Policies and actions to aid CCU products to achieve market cost-competitiveness

 Multi-sectoral project linkages	• Support the development of projects across multiple sectors to drive economies of scale for infrastructure roll-out (e.g. low carbon hydrogen for transport or CCUS/BECCS for power) • Facilitate innovation and demonstration projects deploying renewables, green hydrogen and carbon capture to lower costs in the CCU chain
 Financial incentives and mechanisms	• Introduce policies which level the playing field for CCU routes by remunerating their sustainability benefits (e.g. performance based incentives for higher mitigation potential technologies) • Utilise carbon pricing or operational subsidy schemes, or influence their adoption at the national level (e.g. carbon tax, ETS, tax credits)

4.4 Driving large-scale deployment

Despite achieving market demand and cost-competitiveness, high TRL CCU routes may still face barriers to large-scale deployment. This may include shortages in a skilled labour force or in the technology's supply chain. Specific regions should also consider the drivers to attract new investment opportunities for relevant CCU plants. Table 6 below highlights the final set of identified policies and actions which could be used to enable the roll-out of successfully commercialised CCU routes.

Table 6 Policies and actions to enable large-scale CCU deployment

 Skills development and supply chain	• Identify skills shortages and gaps in the workforce by studying key CCU technology supply chains • Work with training establishments to develop and expand appropriate training courses • Engage with technology suppliers to showcase the market growth in equipment for identified CCU routes, supported by public regional government targets or commitments
 Investment attraction	• Offer public procurement contracts for low carbon products (e.g. cement) • Facilitate project development through pre-planning designated land, streamlining permitting processes, and supporting electricity grid connections or dedicated renewable supplies • Engage with financiers on successful commercial models to support investment in new CCU plants

4.5 Regional recommendations for adopting CCU supporting actions

For the supportive actions and policies identified in the previous sections, applicability to specific regions will be different dependent upon regional characteristics and on the administrative capabilities of each region. For instance, a region may be a product creator or a product user depending on its dominant local industries. Figure 5 provides an overview of the areas in which regional governments can play a closer role in supporting the commercialisation and deployment of CCU technologies.

Figure 5: Categories of actions that regional governments can take to support CCU adoption

Further details and examples on the categories of enabling actions shown in Figure 5 are provided below. Regional governments are well placed to support CCU adoption through:

- **Provision of direct funding or subsidies**, or supporting applications for these at the national level. At the regional level, these can take the form of innovation grants for RD&D or operational subsidies for early CCU projects/plants. For example, European regional governments can support applications for the EU Horizon 2020 programme, which has already provided funding to a range of CCU technology developers and researchers (e.g. Carbon Recycling International[36], Carbon8 Systems[37]).

- **Facilitating knowledge sharing and collaborations or partnerships** between emitters, potential CO_2 utilisers, infrastructure owners, technology developers, research organisations and purchasers or consumers of end-products. For instance, in the German state of North-Rhine Westphalia, the IN4Climate platform is bringing together project partners (energy services company Uniper and the German Aerospace Center - Institute for Solar Research) for a feasibility study on identifying scalable regional CCU projects.[38]
- **Streamlining planning and permitting processes** for CCU product trials, technology demonstration projects, or the development of related infrastructure (e.g. hydrogen/CO_2 transport). For large-scale deployment, regional governments can investigate likely locations for potential capture and utilisation sites and work with local governments to identify planning policy gaps and challenges.
- **Implementing policy interventions at the regional level**, such as green procurement programmes for low-carbon products (e.g. cement) or low emission product standards (e.g. for fuels). Regional governments can act as early adopters of new policy recommendations and demonstrate their feasibility and economic viability, thereafter enticing national governments to take similar measures. For example, California's Low Carbon Fuel Standard sets a declining target for the carbon intensity of supplied fuel, recognising the lower emission benefits of CCU-derived transport fuels.
- **Influencing national governments** on support for CCU projects/infrastructure, as well as stricter industrial emissions limits and carbon taxes or trading schemes. Furthermore, regional governments can engage closely with their national counterparts to gather evidence on promising CCU routes that achieve both valuable emissions reductions and provide additional co-benefits to local economies and communities (e.g. employment, export potential, reduced waste and raw material extraction, etc.). Regional governments could also influence CO_2 accounting practices to be aligned internationally.
- **Supporting local workforces and supply chains** by identifying skills shortages and gaps in the transition to large-scale CCU adoption and/or development of nascent industries. Regional governments can focus support towards workforce training, such as repurposing skills from declining industries (e.g. fossil fuels). Thereafter, further engagement with local industries can be undertaken to run awareness campaigns on the anticipated growth demands for new skills and technologies.

5 Conclusion

This annex to the ITP's Fostering Disruptive Innovation study has highlighted disruptive CCU routes with the potential for regional support and development. A review of promising CCU technologies has demonstrated a range of accelerated mineralisation and catalytic conversion pathways to produce chemicals, fuels, materials and polymers. Pathways differ by their level of commercialisation (i.e. TRL) and market potential. Two deep dives into the utilisation of CO_2 to produce methanol and CO_2 curing in concrete production explored additional factors such as costs, optimal plant siting, existing and future policy support, and emissions mitigation. Regional deployment of specific CCU routes will depend on a number of influencing factors, such as costs for low-carbon renewables and the growth of hydrogen economies. Despite the barriers and gaps that exist today, this annex has identified key supporting actions and policies which regional governments can use to foster disruptive innovation in CCU deployment, such as facilitating knowledge sharing and partnerships, implementing regional-level policies, streamlining permitting processes and supporting local supply chains.

[36] CirclEnergy 2019-2021: Production of renewable methanol from captured emissions and renewable energy sources, for its utilisation for clean fuel production and green consumer goods [LINK]
[37] Carbon8 2019: Capturing and adding value to CO2 & hazardous waste to produce valuable aggregates for construction [LINK]
[38] IN4Climate 2020, Press Release: With IN4climate.NRW, the state is funding two new projects on climate protection in industry with more than 750,000 euros [LINK]

Appendix - preliminary research of five CCU options

Option 1: CO_2 cured concrete (focus on CO_2 curing of alternative cements)[39]

Utilisation Pathway	Applications	Impact	Market Factors
Accelerated mineralisation of alternative cement (or standard cement)	Pre-cast concrete blocks, slabs, pipes. (or ready mix concrete)	Permanent sequestration. Avoids cement emissions. Reduced quarrying.	Pre-cast concrete market is large. CCU could be cost-competitive. Developers: Solidia Technologies (and CarbonCure)

Additional details

- **Process:** The pre-cast concrete is made using a special cement high in calcium silicate minerals. This cement hardens ('cures') through reacting with CO_2 rather than water. This is achieved using an increased CO_2 atmosphere within a curing chamber.
- **Efficiencies:** The special cement is produced using lower temperatures than regular cement, reducing fuel consumption. The concrete blocks cure within 24 hours in a CO_2 chamber compared to 24 days for normal curing.
- **Impact on emissions:** Per tonne of cement, 230 kg of CO_2 is permanently sequestered and 245 kg of CO_2 could be avoided (30% reduction in cement production emissions). Overall reducing emissions from cement by up to 70%.

Highlights

- **Applicability to regions:** cement is a key industry for multiple regions and concrete tends to have localized markets, so regional governments could play a key role in their development.
- **Large markets:** concrete is the most commonly used construction material with a variety of applications.
- **Support opportunities:** public procurement is a potential support policy; this could be implemented at the regional government level.
- **Advanced development:** Technology is in advanced stage of development, having undergone trials, been developed commercially and received market interest.

Option 2: Waste-to-Building Materials (aggregates, concrete)[40,41,42]

Utilisation Pathway	Applications	Impact	Market Factors
Accelerated mineralisation of waste residues.	Lightweight aggregate for use in concrete blocks. (Pre-cast concrete)	Permanent sequestration. Reduced quarrying. Waste treatment & reuse. (avoids cement emissions)	Relatively large aggregates market. Cost-savings for waste treatment. Multiple developers at advanced stages (e.g. Carbon8 Systems)

Additional details

- **Waste treatment:** Around 2 Gt of alkaline wastes are produced globally each year. The route uses CO_2 to stabilise wastes, allowing them to be safely re-purposed and avoiding landfill or 'waste pile' disposal.
- **Avoidance of fees:** The typical costs of waste treatment for safe disposal ('gate fees') can be considerable. The CCU route avoids these fees and can be an alternative, lower-cost waste treatment solution.
- **Straight forward & integrated process:** Technology can be installed onsite as a containerised system, using waste residues and CO_2 from the same plant.
- **Impact on emissions:** Permanent sequestration of CO_2 with potential to be carbon negative.

Highlights

- **Applicability to regions:** waste residues can come from cement plants (fly ash) or steel plants (slag) which are relevant to several regions. Aggregate is an important construction material and markets tend to be localized.
- **Co-benefits:** include avoiding landfill of wastes and quarrying of primary aggregate. Relevancy to regions with limited land availability.
- **Support opportunities:** public procurement and/or existence of high waste-disposal fees are potential drivers for the route; these could be implemented at the regional government level.
- **Advanced development:** Examples of technology deployed commercially (e.g. VICAT France)

[39] Based on Solidia Technologies approach [LINK]. Note that CarbonCure is also in advanced development, but the approach sequesters limited CO_2 with the majority of emission reductions from lower cement use [LINK].
[40] Based on the Carbon8 Systems waste-to-aggregate approach [LINK]. Several other routes and developers exist.
[41] Gnomes et al. 2015, Alkaline residues and the environment [LINK]
[42] Carbon8 Systems 2020, Press Release: Carbon8 Systems to deploy its pioneering technology at Vicat Group cement company in France [LINK]

Option 3: CO_2 to Methanol[43,44,45]

Utilisation Pathway	Applications	Impact	Market Factors
Catalytic reaction with hydrogen.	Solvent, chemical intermediate, gasoline blending, M100 fuel, methanol-to-olefins	Avoids fossil-derived methanol. Use of CO_2 offsets end-of-life emissions.	CCU has cost premium over fossil-derived methanol. Main developer: Carbon Recycling International (sells 'Vulcanol' product)

Additional details

- **Varied end-uses:** methanol is used as a building block for many higher value chemicals and fuel additives. It can also be used as a feedstock for olefins (used to make plastics) and gasoline. Global methanol production is around 100 Mt per year (20% used for fuels).
- **Gasoline blending:** CCU methanol could be used as a sustainable fuel for gasoline blending, with blends of 3-5% permitted in Europe and the US.
- **Costs:** Estimates suggest CCU methanol is at best-case twice the cost of fossil-derived methanol.
- **Emissions:** Avoidance of 2 t of CO_2 / t methanol may be possible (1.5 t utilised, 0.5 t due to lower emission production route) if renewable electricity is used .

Highlights

- **Applicability to regions:** Diverse and varied applications offer potential relevance to many regions' industries across the chemicals and fuels sectors.
- **High interest, many projects:** Multiple funded pilot projects in Europe, and the focus of many papers.
- **Hydrogen / Power-to-X:** Opportunity to convert electricity / hydrogen to an alternative energy vector. Links to hydrogen as a disruptive technology.
- **Support opportunities:** sustainable fuels blending obligations or targets are potential drivers for market uptake. Enablers could be supporting related deployments of renewables or hydrogen production. These could be implemented at the regional level.

Option 4: CO_2 to Hydrocarbons (focus on F-T syncrude -> diesel, gasoline, jet-fuel)[46,47]

Utilisation Pathway	Applications	Impact	Market Factors
Catalytic reaction with hydrogen.	Drop-in fuels: diesel, gasoline, jet fuel	Avoids crude oil extraction. Use of CO_2 partially offsets combustion emissions.	Strong demand for sustainable fuels. CCU not cost competitive. Several developers & projects. Diverse applications.

Additional details

- **Process:** Syngas is first produced from CO_2 and hydrogen. This is then converted, using established Fischer-Tropsch (F-T) synthesis, to a synthetic crude oil which can be refined to give a range of hydrocarbons.
- **Costs:** Estimates suggest the route is 6 times more expensive than fossil-derived fuels in the near-term and 2.5 times greater in the long-term.
- **Emissions:** Emissions vary significantly depending on the emission intensity of electricity for electrolysis, and avoidance varies with the counterfactual.
- **Developments:** Several developers exist (e.g. Sunfire) with investor interest in the area. There are plans for an industrial scale plant in Norway.

Highlights

- **Applicability to regions:** There are large potential markets for CCU hydrocarbons in each region, for example as fuels in aviation, marine or heavy-duty truck sectors. Refining is a relevant industry to several regions.
- **Use of existing infrastructure:** The route could make use of existing refineries to process synthetic crude. The fuels are 'drop-in' substitutes using existing distribution systems and vehicles.
- **Support opportunities:** sustainable fuels blending obligations or targets are potential drivers for market uptake. Enablers could be supporting related deployments of renewables or hydrogen production. These could be implemented at the regional level.

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43 Using 2020 data from the MMSA via the Methanol Institute [LINK]
44 IEA AMF webpage on Fuel Information: Methanol [LINK]
45 Perez-Fortes et al. 2015, Methanol synthesis using captured CO_2 as raw material [LINK]
46 IEA 2019, Putting CO_2 to Use [LINK]
47 Norsk e-Fuel 2020, Press Release: Norsk e-Fuel is planning Europe's first commercial plant for hydrogen-based renewable aviation fuel in Norway [LINK]

Option 5: CO_2 to Polyols (focus on polyurethane application)[48,49]

Utilisation Pathway	Applications	Impact	Market Factors
Catalytic reaction with higher chemicals (epoxides)	Flexible & rigid foams Coatings & adhesives	CO_2 partially replaces fossil-derived epoxides in the polyol. Reducing fossil consumption.	Potential to be cost-competitive. Advanced stages of development with commercialised products.

Additional details

- **Process:** CO_2 is incorporated into polymer backbones as a partial substitute for fossil-derived epoxide feedstocks. The CO_2 content can be tuned for different material properties up to 50% by weight.
- **Costs:** The route offers opportunities for cost reductions through lowering epoxide use.
- **Impact on emissions:** CO_2 is temporarily sequestered and emissions from epoxides are avoided. Avoidance of 0.4-0.6 t CO_2 per t polyol has been estimated.
- **Developments:** A few developers including established companies (e.g. Covestro). Technology has been demonstrated at pilot scale with product testing ongoing.

Highlights

- **Applicability to regions:** Polyols are traded so the plants could be located in any region. Existing skills could exist in regions as the production route uses standard chemical and polymer processing technologies.
- **Diverse applications:** existing applications of CCU polyols include mattresses and furniture upholstery. Foams from CCU polyols are of interest for use in vehicle interiors.
- **Market interest:** The possibility for cost-competitiveness combined with applications in higher value products (e.g. vehicle interiors) could offer market opportunities.

[48] Kamphuis et al., 2019. CO_2-fixation into cyclic and polymeric carbonates: principles and applications. [LINK]
[49] Von der Assen, 2014. Life cycle assessment of polyols for polyurethane production using CO_2 as feedstock [LINK]