Technology Collaboration Programme
by iea

Evaluating technology options to mitigate greenhouse gas emissions

IEAGHG Technical Report
2021-02
November 2021

CO_2 as a Feedstock: Comparison of CCU Pathways

IEA GREENHOUSE GAS R&D PROGRAMME

International Energy Agency

The International Energy Agency (IEA), an autonomous agency, was established in November 1974. Its primary mandate was – and is – two-fold: to promote energy security amongst its member countries through collective response to physical disruptions in oil supply, and provide authoritative research and analysis on ways to ensure reliable, affordable and clean energy for its 30 member countries and beyond. Within its mandate, the IEA created Technology Collaboration Programmes (TCPs) to further facilitate international collaboration on energy related topics. To date, there are 38 TCPs who carry out a wide range of activities on energy technology and related issues.

DISCLAIMER

COPYRIGHT

ACKNOWLEDGEMENTS AND CITATIONS

This report describes work undertaken by Element Energy on behalf of IEAGHG. The principal researchers were:

- Antonia Mattos
- Amelia Mitchell

To ensure the quality and technical integrity of the research undertaken by IEAGHG each study is managed by an appointed IEAGHG manager. The report is also reviewed by a panel of independent technical experts before its release.

The IEAGHG manager for this report was: Jasmin Kemper

The expert reviewers for this report were:

- Aïcha El-Khamlichi, ADEME
- Paul Zakkour, Carbon Counts

The report should be cited in literature as follows: 'IEAGHG, "CO_2 as a Feedstock: Comparison of CCU Pathways", 2021-02, November 2021.'

Further information or copies of the report can be obtained by contacting IEAGHG at:

IEAGHG, Pure Offices, Cheltenham Office Park
Hatherley Lane, Cheltenham,
GLOS., GL51 6SH, UK

Tel: +44 (0)1242 802911
E-mail: mail@ieaghg.org
Internet: www.ieaghg.org

CO_2 AS A FEEDSTOCK: COMPARISON OF CCU PATHWAYS

The aim of this study is to present a holistic assessment of the viability (both technically and from a market perspective) of carbon capture and utilisation (CCU) routes and to identify areas of strength and weakness within individual routes, compare different CCU pathways, and identify common drivers, barriers, and enablers. The results of this study will be of interest to the technical community, as well as industry and manufacturers.

The study assessed commodities across four different CCU categories (building materials, chemicals, polymers and fuels) regarding their mitigation potential, market uptake potential, technical scalability and other impacts.

Key Messages

- Almost all CCU routes showed potential for lower life cycle emissions per tonne of product compared to their counterfactual. The potential scale for deployment was much greater for fuels and building materials than for chemicals and polymers, which typically had existing markets orders of magnitude smaller.
- For fuels, annual abatement levels greater than 1 $GtCO_2$-eq could be achieved for direct replacement 'drop-in' fuels. For building materials, annual abatement levels greater than 100 $MtCO_2$-eq could be achieved. CCU building materials also have potential to offer negative emissions when CO_2 is sourced from direct air capture (DAC). With the exception of methanol, the total mitigation potential of polymers and chemicals was limited to below 20 $MtCO_2$-eq per year.
- Most CCU routes within the chemicals and fuels categories were found to be considerably more expensive than conventional fossil-based production routes, due to high energy requirements for green hydrogen feedstock, low yields and high catalyst costs. CCU building materials and polymers can offer cost reductions.
- There are a range of potential co-benefits (e.g. re-use of waste residues, raw materials reduction, safer production process, improved product properties, energy storage) for CCU routes but there can also be trade-offs (e.g. high energy demand, additional land-use, increased water consumption).
- Deployment of CCU routes may be more favourable in regions with: (i) low-cost or extensive availability of renewable energy; (ii) high cost or lack of available fossil resources; or (iii) significant low-carbon ambition coupled with political or regulatory mechanisms. The current distribution of CCU R&D projects is concentrated mostly in the EU and the US.
- CO_2 utilisation opportunities are diverse, and each route has its own specific drivers, barriers, and enablers. There are, however, some common themes that span across, e.g.: regulations such as mandates or standards, financial provisions, policies that level the field by recognising sustainability benefits, sustainable product development, regional energy availability, costs.
- Recommendations:
  - Report sufficient data to allow for life cycle and techno-economic assessments (LCA and TEA).

- Highlight priority areas for CCU development and identify end-uses where CCU is expected to be a necessary component of future decarbonisation pathways.
- Engage with the public and policy makers to improve understanding of the benefits and limitations of CCU routes.
- Increase awareness of upstream emissions in supply chains and identify opportunities to switch to more sustainable production routes.
- Introducing support mechanisms that allow CCU to receive recognition for sustainability benefits.
- Incorporate CCU products appropriately into existing support schemes, regulations, and product standards.
- Provide funding for research programmes, demonstration projects etc.
- Develop and clarify frameworks for the carbon accounting of CCU routes.

Background to the Study

A range of carbon dioxide capture technologies have been developed, including amine-based routes and calcium looping methods, some of which are now considered to be at technology readiness level (TRL) 9. These technologies have been deployed across the world in large-scale carbon capture, utilisation and storage (CCUS) projects, permanently storing the CO_2 in geological formations, which in 2020 had a capture and storage capacity of 40 $MtCO_2$ per year. Direct air capture technologies, capable of capturing CO_2 directly from the atmosphere, have recently been developed and demonstrated.

As well as storing the CO_2 in geological formations, there is increasing interest in the chemical transformation of captured CO_2 to value-added products, such as building materials, chemicals, polymers, and synthetic fuels. This is driven partly by goals to increase sustainability, lower emissions, and the move towards more circular production routes. Developments have also been driven by realisations that producing some products using CO_2 as a feedstock could lead to improvements in the product or the process, such as enhanced properties or lower feedstock costs. CO_2 is already used extensively for urea manufacture in the fertiliser industry, for enhanced oil recovery (EOR), and for food and beverage production, with other conventional applications including use in fire-extinguishers, greenhouses, and cooling systems. Carbon capture and utilisation (CCU) refers to CO_2 utilisation in which the supplied CO_2 is captured either from an emission point source (e.g. fossil fuel combustion in an industrial plant) or directly from the atmosphere (DAC). With large volumes of CO_2 projected to be captured in the longer term, CCU and CCS can play complementary roles in climate change mitigation.

For many utilisation routes, CO_2 sequestration is only temporary with utilised CO_2 being emitted to the atmosphere as the product is combusted or degrades at its end-of-life. Fuel products may last for less than a year, chemicals less than 10 years, and polymers less than 100 years. At the end of the product's life, the carbon atoms contained within these products often enter the atmosphere as CO_2, with exceptions where this carbon is captured and stored permanently, e.g. in building materials. In absolute terms, these re-emitting CCU routes are therefore at-best carbon neutral but typically net-positive in emissions when their entire life cycle is considered.

Scope of Work

IEAGHG commissioned Element Energy, UK, to investigate a breadth of CO_2 utilisation opportunities that allow CO_2 to be used as a feedstock in the production of building materials, chemicals, polymers, and fuels. The intention is to present a holistic assessment of the routes viability (both technically and from a market perspective), the effect on CO_2 emissions and any additional impacts. The aim is to identify areas of strength and weakness within individual routes, compare different CCU pathways, and identify common drivers, barriers, and enablers. The scope of work consisted of the following tasks:

1. Provide a comprehensive review of available literature and clearly compare different CCU pathways used to produce fuels, chemicals, polymers, and construction materials.
2. Consider the strengths and weaknesses of CO_2-conversion routes, focusing on the CO_2 mitigation potential and other benefits.
3. Conduct independent and impartial analysis, without dismissing or promoting certain utilisation options but rather determining the potential of each CCU option.
4. Identify key barriers, enablers and drivers for the deployment of CCU at scale.
5. Determine the RD&D, policy, and regulatory gaps required to be closed.

This study was carried out in parallel with 'CO_2 utilisation reality check: Hydrogenation pathways', which provides a more detailed look at factors impacting the mitigation potential, costs, and energy demands of methanol, middle distillate hydrocarbons, and formic acid.

Findings of the Study

Methods and approach

The overall aim was to assess commodities under four primary criteria:

- CO_2 mitigation potential: The ability of the CCU route to lead to emissions abatement in the future if there are no technology or economic barriers.
- Market uptake potential: The ability of the CCU route to have an established future market in a low-carbon world if there are no technology barriers.
- Technical scalability: The ability of the CCU route to deploy globally or at a large scale, if there is significant market demand.
- Other impacts: The extent of additional impacts that would occur through deployment of the CCU route.

A set of sub-criteria were identified based on broader factors that influence success in each of these areas. These sub-criteria were then investigated in the same manner for all commodities to ensure a fair and holistic comparison. The influencing sub-criteria are shown in Figure 1.

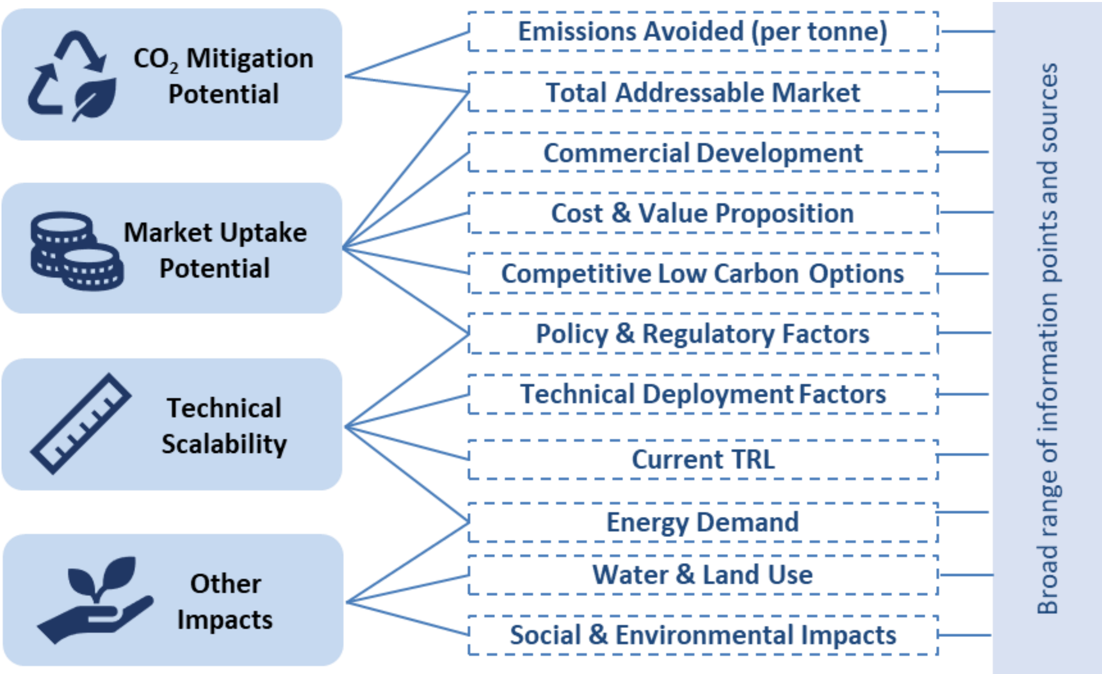


Figure 1 Approach for the assessment of CCU commodities: selection of sub-criteria influencing each of the primary criteria

A total of 12 CO_2 utilisation opportunities were investigated across the four categories, see Table 1. These were selected to demonstrate a wide range of applications with a variety of benefits and trade-offs.

Table 1 Overview of investigated pathways (Market size indicates the 2019/2020 production of conventional product in units of tonnes of product to provide an indication of scale.)

Category	Commodity	Market Size	Utilisation Method(s)
Building Materials	Concrete	30 Gt	Forming mineral carbonates
	Aggregates - Manufactured	1 Gt	Forming mineral carbonates
Chemicals	Methanol - Chemical Intermediate	80 Mt	Hydrogenation
	Formic Acid	1 Mt	Hydrogenation / Electrochemical reduction
	Dimethyl Carbonate (DMC)	90 kt	Reacting CO_2 and epoxides / Reacting CO_2 and methanol
Polymers	Polycarbonate	4 Mt	Reacting CO_2 and epoxides
	Polyols for Polyurethane	12 Mt	Reacting CO_2 and epoxides (catalytic co-polymerisation)
Fuels	Middle Distillate Hydrocarbons	3 Gt	Hydrogenation
	Synthetic Methane	2 Gt	Hydrogenation
	Dimethyl Ether (DME)	500 Mt	Hydrogenation
	Ethanol	100 Mt	Electrochemical reduction
	Methanol - Gasoline Blending	30 – 170 Mt	Hydrogenation

A simplified scoring system for each sub-criterion was selected to allow a high-level comparison of all routes. Commodities were assessed on each sub-criterion and given scores to indicate whether they performed well (area of strength) or not so well (area of weakness). The scores follow a 1-5 scale with higher numbers used to show a more positive, beneficial, or stronger result. For the sub-criteria assessed via comparative life cycle assessments (LCAs), a score of 3 was given if the impact of the CO_2 utilisation route was comparable to the counterfactual, with higher/lower scores given for better/worse impacts respectively. The sub-criteria scores are combined to give a high-level score for each of the primary assessment criteria. The approach used gives the primary criterion a score calculated from the average of the sub-criteria scores. Other options such as products and weighted averages were considered. However, there is limited justification for the weightings, and for the purpose of the high-level comparison an average was deemed appropriate. In most cases, a good current performance in all sub-criteria is not essential for future success as actions can be taken to improve sub-criteria scores. Therefore, an average approach highlights the extent to which further support is needed, without unnecessary penalties for underperformance in a single area. The scoring system is used as a simplified tool to highlight a commodity's strengths and weaknesses. It is not intended as a way to ultimately rank commodities. There are many variables impacting the success of CCU technologies, and these are likely to vary both temporally and regionally. The scores are based upon the authors' interpretations of publicly available data and in some cases high level estimations where data was not available.

Assessment sheets for each commodity

The following pages provide assessment summary sheets with the scorings for each investigated commodity.

Assessment: CO_2 Cured Concrete

Sub-criteria score

Mitigation Potential (Score: 5)

Emissions Avoided[a]: 5

The injection of CO_2 during curing of conventional concrete results in 4-6% lower emissions, corresponding to an abatement of 7-10 kg per tonne of concrete. This predominantly results from a reduction in cement consumption rather than CO_2 sequestration.

4-6% reduction

Cradle-to-gate GWP reduction cf. counterfactual.

Total Addressable Market[b]: 5

The global concrete market is currently estimated at 30 Gt with further growth projected. The market is split between ready-mix and pre-cast concrete. The CO_2 curing route assessed is able to address both segments.

30 Gt / yr

Todays global concrete market

Market Uptake Potential (Score: 5)

Commercial Development[c]: 5

The assessed route has been commercialized by CarbonCure, a company now in the growth phase. The technology is used in commercial operations by several cement manufacturers with installations at over 200 sites globally. The development of other similar CCU routes indicates market interest.

Policy & Regulatory Factors: 4

No significant barriers but limited support. The route could scale without support, but policy could enable increased demand by placing requirements on CO_2 footprint for new buildings and construction materials.

Total Addressable Market 5

Low Carbon Competition: 5

None known. CCS at a cement plant is an option but this doesn't displace the CO_2 curing route.

Cost & Value Proposition: 5

Cost reductions result from the lower cement requirements. Additional value from improved efficiency with quicker curing times and potential for an enhanced product performance.

Scalability (Score: 5)

Policy & Regulatory Factors 4

Technical Deployment Factors: 5

Systems are modular and the technology is straight-forward. The CarbonCure technology is installed as a retrofit at existing facilities with minimal disruption. It is possible that the dispersed nature of concrete production could present challenges for CO_2 distribution.

Current TRL: 5

Technology has been adopted at several sites.

TRL 9 | Multiple At-Scale Operations

Energy Demand: 5

Low energy requirements for the process as carbonation is exothermic. Reduction in lifecycle energy consumption dominated by reduction in cement consumption.

Low Energy Demand

Other Impacts (Score: 4)

Water & Land Use: 4

Water use is similar for most production steps (concrete mixing, aggregate preparation) however overall water use is lower due to reduced cement use. Land use is similar, with reductions in cement use balanced by potential for increased use of aggregates.

Reduced Water Consumption

Energy Demand 5

Social & Environmental Impacts: 5

Potential biodiversity improvements due to reduced mining and reduced waste associated with some routes.

(a) CarbonCure (Monkman) 2017, Calculating Sustainability Impacts of CarbonCure Ready Mix
(b) ICEF 2017, Carbon Dioxide Utilisation (CO2U). ICEF Roadmap 2.0.
(c) Analysis of producers listed at: https://www.carboncure.com/producers/ [accessed Dec 2020]

Assessment: Aggregate from Waste

Sub-criteria score

Mitigation Potential (Score: 5)

Emissions Avoided[a]: 5

The route offers permanent sequestration of CO_2, with claims that more CO_2 is sequestered than is emitted over the aggregate's lifetime. One product claims an absolute GWP of -44 $kgCO_2e/t$ aggregate.

> 100%

Reduction in GWP cf. counterfactual per tonne aggregate

Total Addressable Market[b]: 4

The accessible markets for CCU aggregates are that of the lightweight or manufactured classes of aggregate. The existing market for this type of aggregate totals approximately 1 Gt with demand exceeding supply in some regions.

1 Gt / yr

Todays manufactured aggregate market

Market Uptake Potential (Score: 4)

Commercial Development: 4

CCU technologies have been used in commercial facilities since 2012. Demand exists from industries that wish to avoid waste disposal fees. Carbon8 Systems obtained a contract for delivery of its technology to a global cement manufacturer. Several other companies are commercializing their technologies including Carbicrete and ORBIX.

Policy & Regulatory Factors: 3

Dependency on high waste disposal fees and end-of-waste regulations. Policy could increase demand by placing requirements on CO_2 footprint for new buildings. Product specifications can act as a barrier for sale of the aggregates.

Total Addressable Market 4

Low Carbon Competition: 5

The CCU route is distinct in its business model for processing waste.

Cost & Value Proposition: 5

Value gained from avoidance of waste-disposal fees and potential to extract valuable metals from waste. The resultant aggregate can be sold at a competitive market price as it is not the main revenue driver.

Scalability (Score: 4)

Policy & Regulatory Factors 3

Technical Deployment Factors: 4

The technology is straight-forward and modular, with the potential to install a containerized system at an existing site. Waste residues are required as a feedstock, which may restrict deployment locations and scale.

Current TRL: 5

Deployment of 3 at-scale operations in the UK, one operational since 2012.

TRL 9 | Multiple At-Scale Operations

Energy Demand: 3

Energy consumption will depend upon the pre-treatment and transportation of wastes. The carbonation reaction is exothermic and overall energy demand may be similar to the existing route (low).

Low

Other Impacts (Score: 4)

Social & Environmental Impacts: 5

Benefits include the re-use of waste material, the potential for simultaneous recovery of minerals, and a reduction in mining of primary aggregate.

Energy Demand 3

Water & Land Use: 5

Reduction in land use – waste disposal, mining. Water use expected to be lower.

(a) OCO Technology FAQs

(b) Assuming a global aggregate market of 30-50 Gt (ICEF 2017) with the same percentage (2%) of manufactured/lightweight aggregates as produced in the EU in 2017, given by 'UEPG Provisional Estimates of Aggregates Production - 2018 Data'

Assessment: Methanol as a Chemical Intermediate

Sub-criteria score

Mitigation Potential (Score: 3)

Emissions Avoided[a]: 4

CCU methanol has a lower global warming impact than fossil methanol if low-carbon electricity is used for water electrolysis. Mitigations of the order of 1.5 t CO_2 avoided per tonne of methanol are reported.

1.5 t CO_2/t

Cradle-to-Gate emission reduction per tonne of methanol

Total Addressable Market[b,c]: 2

Methanol has an existing market of 80 Mt as a chemical intermediate, of which 25 Mt is used for olefins via MTO process. The global polyolefins market is in the region of 200 Mt olefin. This could in theory be accessed by methanol if the MTO process were to be used for all olefins production.

80 Mt / y

Existing market for methanol as a chemical

Market Uptake Potential (Score: 3)

Commercial Development: 4

Commercial interest is focused on CCU methanol as a sustainable fuel. CRI markets its CCU methanol commercially as a fuel in Europe, has a contract to deliver a large-scale plant in China and received private investments from a car manufacturer. Market interest from the chemicals sector is unknown but assumed limited due to the significant cost-premium and lack of market drivers.

Policy & Regulatory Factors: 3

No significant regulatory barriers identified. The chemicals sector has no dedicated support for CCU. The route is not cost competitive so lack of policy support could be a barrier.

Total Addressable Market 2

Low Carbon Competition: 3

Bio-based methanol is an established alternative, although availability of bio-feedstocks may limit its penetration. CCU olefins may compete with bio-based and recycled material routes.

Cost & Value Proposition: 2

The CCU route is not expected to reach cost-parity with fossil methanol, with best-case current costs being at least twice that of fossil methanol.

Scalability (Score: 3)

Policy & Regulatory Factors 3

Technical Deployment Factors: 3

A new plant is required but technology is modular and no significant engineering challenges are envisaged. The route requires large amounts of renewable electricity for hydrogen production, but this can be intermittent.

Current TRL: 4

CRI have a small-scale commercial plant in Iceland and pilot projects for specific applications.

TRL 8 | 4 kt/y Demonstration Plant (2015)

Energy Demand: 1

Green hydrogen production requires large amounts of low cost, renewable electricity.

High Energy Demand

Other Impacts (Score: 2)

Social & Environmental Impacts: 3

Benefits associated with lower use of fossil resources. However, additional impacts (good and bad) from large-scale renewable deployment.

Energy Demand 1

Water & Land Use: 1

Increased land and water use due to need for hydrogen production and renewables deployment.

(a) Bazzanella et Ausfelder 2017, Low carbon energy and feedstock for the European chemical industry. Technical study.
(b) Data is from the MMSA shared via the Methanol Institute, available here: https://www.methanol.org/methanol-price-supply-demand/
(c) MTO = Methanol to Olefins (a process for producing olefins from methanol rather than naphtha cracking)

Assessment: Formic Acid (FA)

Sub-criteria score

Mitigation Potential (Score: 3)

Emissions Avoided[(a)]: 5

The counterfactual route is emission intensive. The CCU process results in significantly lower GHG emissions than the counterfactual route, with optimistic potential to avoid 2t CO_2 per tonne formic acid.

92% reduction

Cradle-to-gate GWP reduction cf. counterfactual

Total Addressable Market[(b)]: 1

The existing market size is small at approximately 1 Mt or less. There is some interest in the use of formic acid in fuel cells or as a hydrogen carrier, which would expand the market opportunity.

1 Mt / yr

Market Uptake Potential (Score: 2)

Commercial Development: 2

Limited Information. Patents for hydrogenation routes have been acquired by companies like BP and BASF.

Total Addressable Market 1

Low Carbon Competition: 5

Properties of FA mean that there is low risk of substitution with alternative chemicals. CCU is a low-carbon route to the produce the same chemical.

Policy & Regulatory Factors: 1

No significant regulatory barriers identified. The chemicals sector has limited support for CCU. The route is not cost competitive so lack of policy support could be a barrier.

Cost & Value Proposition: 2

The route is more expensive (approx. 2.5 times) than the conventional route.

Scalability (Score: 2)

Policy & Regulatory Factors 1

Technical Deployment Factors: 2

A new plant is required with novel engineering expected. The route requires access to renewable electricity. Some options require rare catalyst materials.

Current TRL: 1

Patents have been granted for the hydrogenation route, but further lab research is necessary. Route is not yet validated in relevant environment.

TRL 3 | Lab Research

Energy Demand: 3

CCU could be lower than that of the conventional route, if heating and cooling needs can be offset through integration.

Similar

Other Impacts (Score: 3)

Social & Environmental Impacts: 3

Limited Information.

Energy Demand 3

Water & Land Use: 3

Water and land use are similar to the fossil route.

(a) Perez-Fotes et al. 2015, Formic acid synthesis using CO2 as raw material: TEA, environmental evaluation, and market potential

(b) GCI 2016, Global Roadmap for Implementing CO2 Utilisation

Assessment: Dimethyl Carbonate (DMC)

Sub-criteria score

Mitigation Potential (Score: 3)

Emissions Avoided: 4

There are a wide range of values reported for GWP of both the CCU and conventional routes. Emission reductions are reported for the indirect route (ranging extents). At present the direct electrosynthesis route does not lead to emission reductions due to low yields and energy requirements.

Total Addressable Market[(a)]: 1

The current market for DMC lies in the production of polycarbonates (50%) and as use as a solvent (25%). Future markets include use as a non-toxic methylating agent (substituting toxic dimethyl sulfate and phosgene) and as an octane booster (fuel additive) substituting MTBE.

90 kt / yr

Todays existing market for DMC

Market Uptake Potential (Score: --)

Commercial Development:

Market interest for CCU DMC is unknown. Asahi Kasei developed an indirect CO_2 utilisation route that is used commercially, and is reportedly developing a direct utilisation route for dialkyl carbonates (which could include DMC). However, these routes are developed as the initial step for other reactions (e.g. BPA-PC).

Policy & Regulatory Factors:

No dedicated CCU policy/regulatory support was identified within the chemicals sector. This is not necessarily a barrier as the route has potential to develop without support, if added benefits are valued or if profitable (uncertain).

Total Addressable Market 1

Low Carbon Competition:

None known. Limited data.

Cost & Value Proposition[(b)]: 4

A TEA of the indirect route reported it to be profitable with a payback period of 5 years. The route also yields valuable by-products.

Scalability (Score: --)

Policy & Regulatory Factors

Technical Deployment Factors:

Limited information.

Current TRL:

Research is ongoing to optimize the final separation of DMC, improve yields and reduce energy consumption.

Energy Demand:

Current low-levels of development mean that there is a large energy requirement for product separation.

Higher Energy Demand

Other Impacts (Score: --)

Social & Environmental Impacts:

Limited information.

Energy Demand

Water & Land Use:

The process is expected to have increased land and water use.

(a) Garcia-Herrero et al. 2016, Environmental Assessment of Dimethyl Carbonate Production: Comparison of a Novel Electrosynthesis Route Utilizing CO2 with a Commercial Oxidative Carbonylation Process

(b) Souza et al. 2014, Production of DMC from CO2 via Indirect Route: Technical Economical Environmental Assessment

Some sub-criteria have not been scored due to a lack of information relevant to the applied scoring system.

Assessment: Polycarbonate (BPA-PC)

Sub-criteria score

Mitigation Potential (Score: 3)

Emissions Avoided[(a)]: 4

Developers claim that the route reduces CO_2 emissions by 0.173t CO_2 per tonne of polycarbonate, however a life-cycle assessment was not identified. This value likely equates to the quantity of CO_2 that is utilised per tonne.

Total Addressable Market[(b)]: 1

The CCU product is a direct substitute for existing polycarbonate, a common engineering thermoplastic. The global demand for polycarbonate was 4 Mt in 2017 with growth projected.

4 Mt / yr

Market Uptake Potential (Score: 3)

Commercial Development[(a)]: 4

Six companies had licensed the technology (developed by Asahi Kasei) by 2018 with multiple plants operational or under construction. Developers expected that the technology could take a 25% share of the market, however the market is dominated by 5 key players each using conventional routes.

Technology Licensed | Adopted by small players

Total Addressable Market 1

Low Carbon Competition: 3

Bio-based and recycled polymers may compete with CCU polymers.

Policy & Regulatory Factors: 5

No significant barriers. No dedicated support. The route is cost competitive so could scale without support.

Cost & Value Proposition: 4

It is claimed that the route has economic benefits for both plant costs and feedstock costs. The process has several other advantages over the conventional route which may offer additional value proposition.

Scalability (Score: 4)

Policy & Regulatory Factors 5

Current TRL: 5

150kt plant operational since 2002 in Taiwan. Plants in Russia, Korea and Middle East.

TRL 9 | Operational Industrial Scale Plants

Technical Deployment Factors: 3

Construction of a new plant is required however no significant engineering challenges are envisaged. CCU facilities could be easier to deploy than conventional facilities - e.g. due to permitting requirements.

Energy Demand: 4

Developers claim energy savings over the conventional route due to high yields and improved selectivity.

Lower Energy Demand

Other Impacts (Score: 5)

Social & Environmental Impacts: 5

The route avoids the use of toxic reagents (phosgene, CH_2Cl_2) making it a safer process. All intermediates are recycled leaving no waste products and no need for waste water treatment.

Energy Demand 4

Water & Land Use:

Limited data.

(a) Fukuoka et al., 2007. Green and sustainable chemistry in practice: Development and industrialization of a novel process for polycarbonate production from CO2 without using phosgene.

(b) Kamphuis et al., 2019. CO2-fixation into cyclic and polymeric carbonates: principles and applications.

Some sub-criteria have not been scored due to a lack of information relevant to the applied scoring system.

Assessment: Polyols for Polyurethane

Sub-criteria score

Mitigation Potential (Score: 3)

Emissions Avoided[a,b]: 4

Emission reductions result primarily from reduced consumption of epoxide feedstock, as well as temporary sequestration of captured CO_2. Up to 4 kg of CO_2 can be avoided per kilogram of CO_2 utilized (cradle-to-gate).

11-19 % reduction

Cradle-to-gate GWP reduction cf. counterfactual for polyol of 20wt% CO_2.

Total Addressable Market[c]: 2

CCU polyols are a potential alternative to polyether polyols in the production of PUR. In 2017 the global production capacity for these polyols was 12 Mt with growth projected. The PUR market is estimated at 20 Mt with end-uses split across flexible and rigid foams, coatings, and adhesives.

12 Mt / yr

Market Uptake Potential (Score: 4)

Commercial Development: 4

CCU polyols developed by Covestro (a top player in the existing market) can be purchased in Europe. Saudi Aramco markets two CCU polyol products. Interest exists from automakers for use of these polyols in car interiors. Applications in mattresses and furniture are commercialized.

Large Companies – Existing Market Players

Policy & Regulatory Factors: 5

No significant barriers. No dedicated support. The route is cost competitive so could scale without support. CCU polyols must be tested to ensure their suitability for specific applications, however testing is common for new products.

Total Addressable Market: 2

Low Carbon Competition: 3

Bio-based and recycled polymers may compete with CCU polymers.

Cost & Value Proposition[d]: 4

Claims that CCU polyols offer superior properties at lower or competitive costs when produced at scale. Potential cost savings of 15-30% from the partial replacement of epoxide feedstocks with less expensive CO2 feedstock.

Scalability (Score: 4)

Policy & Regulatory Factors: 5

Technical Deployment Factors: 4

Processes used are very similar to that of existing facilities. For low molecular weight polyols, it may be possible to use existing production facilities with minimal retrofit. Higher molecular weight polyols may require new facilities.

Current TRL: 4

Technology is being demonstrated at small scale in Europe and for product trials in the USA.

TRL 8-9 | 5 kt Demonstration Plant

Energy Demand: 4

Energy reductions possible, dependent upon the balance between energy for CO_2 capture and for the epoxide feedstock.

Lower Energy Demand

Other Impacts (Score: 3)

Social & Environmental Impacts[a]: 4

A reduction in the use of fossil resources of between 13-16% is reported, with other environmental impacts being similar to the conventional route.

Energy Demand: 4

Water & Land Use: 2

Potential increase in land-use requirements, with water consumption remaining similar.

(a) Von der Assen, 2014. Life cycle assessment of polyols for polyurethane production using CO_2 as feedstock: insights from an industrial case study.
(b) Von der Assen, 2015. Environmental potential of carbon dioxide utilization in the polyurethane supply chain
(c) Covestro Capital Markets Day 2018 - Investor Presentation
(d) ECOFYS 2017, Assessing the potential of CO_2 utilisation in the UK

Assessment: Middle Distillates (F-T Fuels)

Sub-criteria score

Mitigation Potential (Score: 5)

Emissions Avoided[(a)]: 5

A study based on the Sunfire demonstration plant reported that emissions are 11 or 28 g CO_2-eq / MJ fuel if the electricity is German-based wind or solar PV respectively. This compares to 87.5 g CO_2-eq / MJ for the fossil route.

70-90% reduction

Cradle-to-grave GWP reduction cf. counterfactual

Total Addressable Market[(b)]: 4

The CCU technology produces synthetic crude that which then undergoes hydrocracking/refining to produce the final fuels, which could be diesel, gasoline or jet fuel. The total existing market for these fuels is estimated at 3 Gt.

3 Gt / yr

Market Uptake Potential (Score: 2)

Commercial Development: 3

Market interest exists. There are plans for an industrial-scale deployment in Norway (Norsk e-fuel). Sunfire have been successful in gaining venture capital from investment rounds. Other companies have demonstrated the technology.

Industrial-Scale Deployment Planned | Venture Capital

Policy & Regulatory Factors: 2

CCU relies on fuel mandates to increase market demand, requiring CCU fuels to be recognized in these mandates. The lengthy and expensive testing and approval process for new fuels can act as a barrier to new entries, especially in aviation.

Total Addressable Market 4

Low Carbon Competition: 1

Established low-carbon options exist for road transport, but CCU fuels are projected to penetrate the heavy-duty trucks market. The main use for CCU fuels is expected to be as an aviation fuel as this market has limited alternatives.

Cost & Value Proposition: 2

CCU is more expensive than the conventional route.

Scalability (Score: 3)

Policy & Regulatory Factors 2

Technical Deployment Factors: 3

Requires a new plant with engineering novelty. Existing distribution infrastructure can be used. Hydrogen production requires access to renewable electricity and fresh water, which could restrict deployment in some regions.

Current TRL: 4

Demonstration plant in Germany. Industrial plant planned for 2023.

TRL 8 | Demonstration Plant

Energy Demand: 1

High level estimates suggest that the CCU route is 15 times more energy intensive than the counterfactual route.

Higher Energy Demand

Other Impacts (Score: 3)

Social & Environmental Impacts: 5

Cleaner burning fuels with reduction in NOx, SOx and particulates. Allows continued use of existing refining assets and vehicle stock.

Energy Demand 1

Water & Land Use: 4

Land use is similar to the counterfactual route whereas water use is significantly lower.

(a) Umwelt Bundesamt, 2016. Power to liquids: Potentials and Perspectives for the Future Supply of Renewable Aviation Fuel

(b) IEA Oil Information 2020

Assessment: Synthetic Methane

Sub-criteria score

Mitigation Potential (Score: 5)

Emissions Avoided[a,b]: 5

It is estimated that the CCU route has 22% of the emissions of the conventional route, with a reduction of 2.2t CO_2-eq per tonne of methane.

78% reduction

Cradle-to-grave GWP reduction cf. counterfactual

Total Addressable Market[c]: 4

Current global natural gas demand is approximately 2 Gt (3 Gtoe). Synthetic natural gas has multiple potential future markets including the existing market, as a transport fuel and as a chemical feedstock.

2 Gt / y

Market Uptake Potential (Score: 2)

Commercial Development: 3

Market interest exists for the use of low-carbon methane (currently biomethane) for transport and heating applications. Audi uses an offset system for selling its (demonstration plant) e-gas to customers via the natural gas network.

Total Addressable Market 4

Low Carbon Competition: 1

There are alternative grid-balancing options including batteries and power-to-hydrogen. As an energy carrier, there is competition from other low-carbon options (such as hydrogen and electrification) but CCU could benefit from allowing continued use of existing assets.

Policy & Regulatory Factors: 1

The route is not cost competitive so would require significant policy support to drive market demand. No regulatory barriers preventing product use are identified.

Cost & Value Proposition[d]: 3

CCU is 4-5 times more expensive than the fossil route, with costs highly dependent upon electricity price. Its value lies in use as a low-carbon energy vector and the grid-balancing potential of power-to-gas.

Scalability (Score: 2)

Policy & Regulatory Factors 1

Technical Deployment Factors: 3

Requires a new plant but can use existing distribution infrastructure. Hydrogen production requires access to renewable electricity and fresh water, which could restrict deployment in some regions.

Current TRL: 4

Multiple pilot-scale projects, with 4 European projects (planned/operational) at greater than 5 MW capacity.

TRL8 | > 5 MW Pilot Projects (4)

Energy Demand: 1

Green hydrogen production requires large amounts of low cost, renewable electricity. Total energy is 20 times conventional.

High Energy Demand

Other Impacts (Score: 2)

Social & Environmental Impacts: 4

CCU provides an opportunity to integrate intermittent renewables into existing energy infrastructure, with no alterations to end-user appliances. Benefits from displacing fossil feedstocks.

Energy Demand 1

Water & Land Use: 1

Increased land and water use is expected due to the requirements for hydrogen production and associated renewables deployment.

(a) Bongartz et al. 2018, Comparison of light-duty transportation fuels produced from renewable hydrogen and green carbon dioxide
(b) BEIS 2020, Greenhouse gas reporting: conversion factors 2020
(c) Based on IEA Natural Gas Information Overview (value for 2019 production convert to Gt)
(d) ECOFYS 2017, Assessing the potential of CO_2 utilisation in the UK

Assessment: Dimethyl Ether (DME)

Sub-criteria score

Mitigation Potential (Score: 4)

Emissions Avoided[a]: 5

Cradle-to-grave greenhouse gas emissions of CO_2-derived DME are approximately 14% of those from DME produced conventionally from natural gas. This equates to reductions of 70 g CO_2-eq per MJ of DME.

86% reduction

Cradle-to-Grave GWP reduction cf. counterfactual

Total Addressable Market[b]: 3

DME currently has uses in household products, aerosol propellants, and paint. A fuel market for DME as a diesel alternative is emerging. Converting the global heavy-duty trucks market to DME would give a market in the region of 500 Mt.

500 Mt / yr

Estimated future DME market if used as an alternative to diesel in trucks

Market Uptake Potential (Score: 2)

Commercial Development: 1

No commercial development known for use of captured CO_2 specifically. Oberon Fuels in the US uses either stranded natural gas or biogas (both mixtures of methane with up to a maximum of 50% CO_2) in a dry reforming process, marketed as renewable DME.

Total Addressable Market 3

Low Carbon Competition: 1

Established alternatives exist. Although DME can allow continued use of existing assets via engine retrofit.

Policy & Regulatory Factors: 2

DME is approved as a transport fuel in some regions. Production of DME by a new CCU route would need to undergo the fuels testing and approvals process.

Cost & Value Proposition: 3

Not expected to be cost competitive with conventional DME route but may realise value for 'sustainability'. Use of DME instead of diesel could reduce the need for expensive diesel particulate filters on truck engines.

Scalability (Score: 2)

Policy & Regulatory Factors 2

Technical Deployment Factors: 3

Requires CCU methanol production – new plants, access to renewable electricity, water requirements. CCU methanol can be used in the existing methanol-to-DME process. Engine retrofits are needed for DME use as a diesel alternative.

Current TRL: 2

The methanol-to-DME process is established with fossil-based methanol. CCU methanol is at TRL8.

Uses Known Processes

Energy Demand: 1

CCU requires significant energy demand for hydrogen production. Energy consumption is much higher than the conventional route.

High Energy Demand

Other Impacts (Score: 3)

Social & Environmental Impacts: 5

Benefits from displacing fossil feedstocks but impacts from renewables deployment. Compared to diesel, DME combustion emissions are lower in CO, SOx and NOx.

Energy Demand 1

Water & Land Use: 3

Limited information available. Estimates of lower water consumption but increased land-use.

(a) Matzen M and Demirel Y (2016). Methanol and dimethyl ether from renewable hydrogen and carbon dioxide: Alternative fuels production and life-cycle assessment

(b) Based on IEA ETP value for heavy-duty truck diesel market

Assessment: Ethanol

Sub-criteria score

Mitigation Potential (Score: 4)

Emissions Avoided[(a)]: 5

Air Co. claims that its process is net-negative, removing 1.5 t CO_2 / t CO_2 utilised as assessed through LCA. However, the details behind this assessment are unavailable and the boundaries are unknown.

Total Addressable Market[(b)]: 3

The dominant end use of ethanol is as a fuel or fuel additive, with other uses being as an industrial solvent, for use in alcoholic beverages and personal care products such as hand sanitizer and cosmetics. The demand for ethanol as a sustainable fuel is growing.

100 Mt / y

Market Uptake Potential (Score: --)

Commercial Development:

Several companies have been involved with developing different CO_2 to ethanol technologies. Air Company have produced and sold CCU products at pilot-scale (Vodka and personal care products). Lanzatech is pursuing ethanol from flue-gas technologies. Market interest for CCU ethanol as a fuel is unclear, but demand exists for bio-ethanol.

Policy & Regulatory Factors: 3

CCU relies on fuel mandates to increase market demand, requiring CCU fuels to be recognized in these mandates. Regulations limit blending percentages.

Total Addressable Market 3

Low Carbon Competition: 1

Established competitive options exist for road transport fuels - EVs and hydrogen FCEVs.

Cost & Value Proposition:

Costs for the electrochemical CCU route will depend upon electricity and CO_2 prices. The Joule process targeted a price of USD 0.32 / L which was competitive at the time. Counterfactual costs are dominated by crop prices which are variable.

Scalability (Score: --)

Policy & Regulatory Factors 3

Technical Deployment Factors:

Limited publicly available information on the technologies. The electrochemical route is expected to require large amounts of renewable electricity and water.

Current TRL:

Air Company have a small-scale facility and a larger demonstration plant being built. Lanzatech plan to build a pilot plant that will use 50% CO_2 as the carbon source.

Small-Scale Pilot

Energy Demand: 2

High level estimate that the CCU energy demand is slightly (10-20%) greater than bio-ethanol.

Small Increase

Other Impacts (Score: 4)

Social & Environmental Impacts: 5

Unlike bio-ethanol, CCU ethanol is not associated with competition for food crops. CCU route does not require fossil-fertilizer and has benefits from lower land-use.

Energy Demand 2

Water & Land Use[(c)]: 5

CCU fuels use approximately 5 times less land than bio-fuels and 100 times less water.

(a) Air Co (2020). Available at: https://aircompany.com/pages/science

(b) Renewable Fuels Association 2019

(c) Umwelt Bundesamt (2016). Power to liquids: Potentials and Perspectives for the Future Supply of Renewable Aviation Fuel.

Some sub-criteria have not been scored due to a lack of information relevant to the applied scoring system.

Assessment: Methanol as a Fuel

Sub-criteria score

Mitigation Potential (Score: 4)

Emissions Avoided[a]: 4

CCU methanol has a lower global warming impact than fossil methanol if low-carbon electricity is used for water electrolysis. Mitigations of the order of 1.5 t CO_2 avoided per tonne of methanol are reported.

1.5 t CO_2/t
Cradle-to-Gate emission reduction per tonne of methanol

Total Addressable Market[b,c]: 3

Low-levels of gasoline blending (3%) give a potential market size of 34 Mt whereas higher-levels (15%) give a market size of 170 Mt. In the longer-term, CCU methanol (or its derivatives) could be used directly as a fuel (100%) with accessible markets being the marine fuels sector (200 Mtoe) and heavy-duty trucks (600 Mtoe).

Market Uptake Potential (Score: 3)

Commercial Development: 4

A CRI demonstration facility (4 kt/y) markets its CCU methanol commercially in Europe. The company has a contract to deliver a large-scale plant in China and has received investments from private companies including a Chinese car manufacturer.

Total Addressable Market 3

Low Carbon Competition: 2

Several established competitive options including bio-fuels, EVs and FCEVs. These have limitations in biofuel availability and requirement of new vehicle stock.

Policy & Regulatory Factors: 3

The high commodity price means the route is reliant on fuel mandates to increase market demand. This type of mandate already exists in some regions. Specifications limiting fuel blending and what types of fuels constitute as 'sustainable' act as a barrier.

Cost & Value Proposition: 3

The CCU route is not expected to reach cost-parity with fossil methanol. Its value proposition is as a sustainable fuel.

Scalability (Score: 3)

Policy & Regulatory Factors 3

Technical Deployment Factors: 3

A new plant is required but technology is modular and no significant engineering challenges are envisaged. The route requires large amounts of renewable electricity for hydrogen production, but this can be intermittent.

Current TRL: 4

CRI have a small-scale commercial plant in Iceland and pilot projects for specific applications.

TRL 8 | 4 kt/y Demonstration Plant (2015)

Energy Demand: 1

Green hydrogen production requires large amounts of low cost, renewable electricity.

High Energy Demand

Other Impacts (Score: 2)

Social & Environmental Impacts: 3

Potential for immediate drop-in to existing vehicle-stock via blending. Methanol has low toxicity compared to ammonia (marine fuels). Cleaner burning than other fuels.

Energy Demand 1

Water & Land Use: 1

Increased land and water use due to need for hydrogen production and renewables deployment.

(a) Bazzanella et Ausfelder 2017, Low carbon energy and feedstock for the European chemical industry. Technical study.
(b) IEA Oil Information 2020 - gives 2018 motor gasoline demand as 1131 Mt
(c) IEA Energy Technology Perspectives 2020 – data on marine fuels and heavy-duty trucks demands

Regional considerations

The future success of CCU technologies will be influenced by a variety of factors, many of which can vary significantly between countries and/or regions. Three factors that could impact the success of multiple CCU routes are fossil resources (availability/dependence), deployment of renewable electricity generation, and policy & regulatory support.

The availability of fossil resources impacts the cost of producing conventional fossil-based chemicals, polymers, and fuels as these are typically derived from fossil-feedstocks. High conventional prices could enable CCU products to be more competitive. Importers of fossil resources, such as Europe, may be concerned about security of supply, acting as a driver for more local CCU production pathways.

Many of the chemical and fuel CCU routes use hydrogen produced from electrolysis, meaning that costs are highly dependent upon the cost of renewable electricity. The ability to deploy renewables and the cost of these renewables is therefore an influencing factor for the uptake of relevant CCU routes. Currently solar PV costs are lowest in North America and the Middle East. Regions where there is limited opportunity for renewables installations may choose to prioritise the use of these renewables for other decarbonisation routes.

CCU routes that are not cost competitive with conventional products are likely to require significant policy or regulatory support to achieve market uptake. Provision of early funding support also enables development of innovative technologies and the deployment of demonstration projects. Support for CCU is more likely to be available in regions with strong climate ambitions. For example, the European Union has the Renewable Energy Directive (RED II), an Emissions Trading System (ETS), and many countries have imposed additional carbon taxes such as Sweden (USD 119/tCO_2) and Switzerland (USD 99/tCO_2).

The development, deployment and uptake of CCU routes may be more favourable in: (i) regions with low-cost renewables or extensive availability of renewable energy (fuels, chemicals); (ii) regions with high cost or lack of available fossil resources (fuels, chemicals, polymers); or (iii) regions with significant low-carbon ambition coupled with political or regulatory mechanisms to incentivise CCU developments and CCU uptake (all routes). According to analysis of the SCOT database, the current distribution of CCU research and development projects is concentrated mostly in the EU (44% of projects) and the US (33% of projects). Figure 2 provides a summary of the considerations discussed in this section for three different key regions: North America, Europe and Asia.

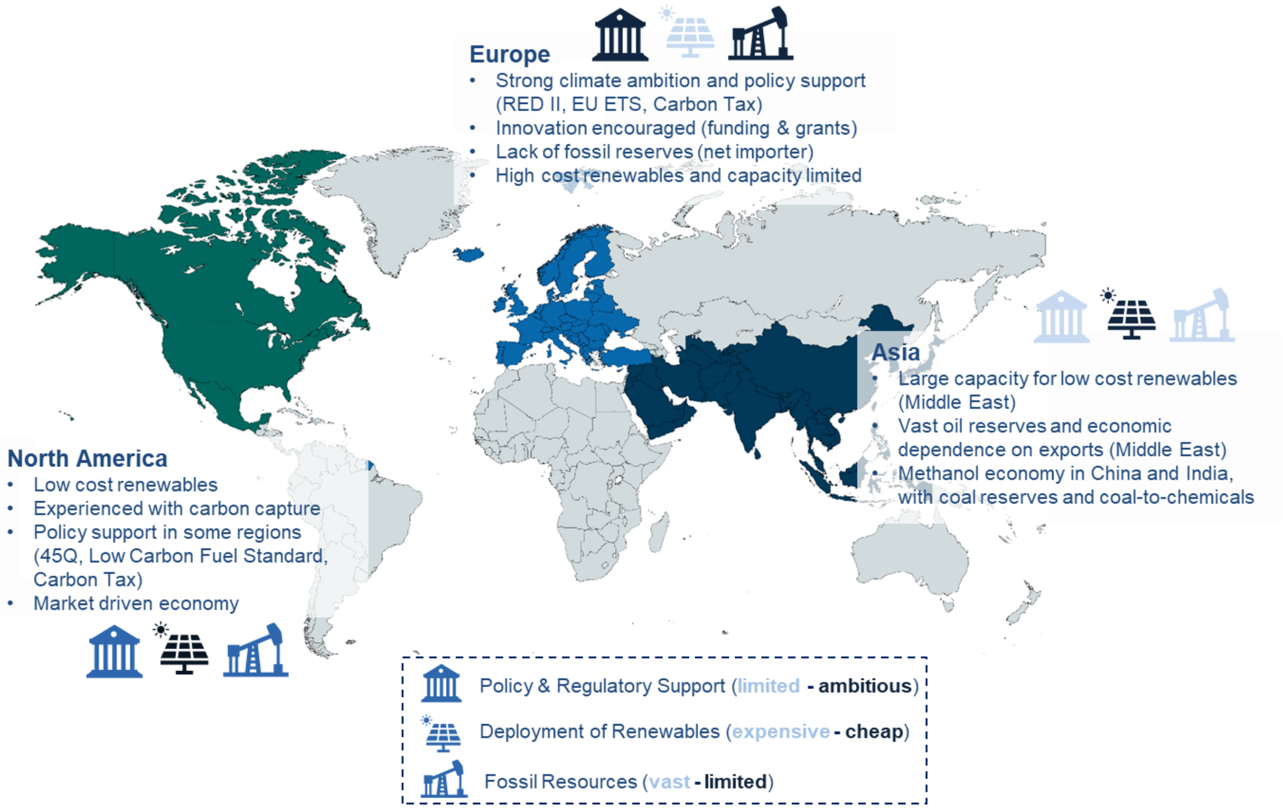


Figure 2 Overview of regional considerations for CCU deployment

Drivers, barriers and enablers

CO_2 utilisation opportunities are diverse, and each route has its own specific drivers, barriers, and enablers. There are, however, some common themes that span across many of the CCU routes assessed. These can be categorised into those relating to regulatory or policy factors, those relating to technical factors, and those relating to market or economic factors, including product competitiveness and market perceptions.

Regulatory and Policy

Regulations such as mandates or standards could act as drivers for the uptake of CCU products, however prescriptive requirements may be a barrier. The introduction of legal requirements for manufacturers or firms to supply or procure a minimum percentage of products from sustainable or low-emission sources can have the impact of increasing demand for these products, offering CCU routes a more viable route to market and fostering innovations. However, the use of prescriptive requirements can inadvertently exclude CCU products, making performance-based regulations preferable. Existing regulations may need to be updated to enable some CCU routes, for example aggregates from waste must be recognised as 'end-of-waste' before use, and increases in blending limits could benefit synthetic fuels.

As with many emerging technologies, the development, demonstration, and uptake of CCU technologies can be facilitated by financial support from governments or institutions. The cost premium of CCU products is currently a barrier for many routes. Policies that allow CCU products to realise value from their sustainability benefits would enable CCU products to be more competitive in the market. For example, carbon pricing mechanisms, such as a carbon tax or emissions trading scheme, or other policy support schemes such as a Contract for Difference style mechanism. Further clarity is needed on how benefits may be realised through carbon accounting.

Technical

Drivers for CCU developments may be environmental, or they may be oriented around improving production processes or creating an enhanced product. Factors such as emission avoidance, the recycling of CO_2, circular economy principles and the avoidance of fossil feedstocks are often cited as motivations for developing CCU routes. There are also examples in which CCU was adopted partially because the production route was superior to existing processes, or because the route produces products that offer enhanced properties compared with conventional products.

Energy availability may be a challenge for deployment in some regions. The CCU routes with high energy demands may face barriers obtaining low-emission intensity electricity, with dedicated renewables likely required to avoid impacting the wider energy system. Deployment of or access to large capacities of renewables for CCU may prove challenging in some regions where costs are high or where there is high competition for renewables.

The approvals process may act as a barrier for some products. Market uptake of CCU products may be reliant on products meeting regulatory requirements or standards, and potentially undergoing lengthy and expensive approvals processes. This may present technical challenges, for example the need to produce large volumes of aviation fuels for testing, the need to meet highly prescriptive criteria, or a lack of available testing facilities. New products will need to demonstrate their suitability for the intended applications before they can be deemed acceptable by industry, with conservative nature of some markets presenting additional barriers.

Market and Economic

The cost of CCU routes can be a key barrier to their adoption. However, a select few routes are driven by cost-savings or improving the value of products. CCU routes for chemicals and fuels currently have much higher production costs than their counterfactuals, acting as a significant barrier to market uptake. There is an opportunity for carbon pricing mechanisms to lower cost premiums. However, to achieve cost-parity much more ambitious carbon prices are needed than those currently adopted. Alternatively, market uptake of sustainable products could be driven by a need to comply with imposed targets or regulations. Some CCU routes in building materials and polymers already have a business case in certain regions without additional policy or regulatory support.

A lack of awareness or engagement with product life cycle emissions and/or a lack of awareness of CCU can act as a barrier. Manufacturers can lack awareness of emissions in their supply chains or product end-uses. They may not consider themselves responsible for these indirect (Scope 3) emissions or may not be able to accurately obtain data on them. Furthermore, the lack of commercial development, clarity, and marketing of CCU may mean that engaged companies do not consider CCU products in decarbonisation plans. Consumer perception is also important, with limited evidence on the impact. The concept of CCU may be perceived negatively by consumers, who may have concerns about the use of CO_2 in products. On the other hand, careful marketing could allow products to use sustainability as a selling point.

Expert Review Comments

Two reviewers from a government related organisation and an independent consultancy provided comments on the draft report. The majority of the comments have been addressed by the contractor, including but not limited to:

- Addition of a box to highlight similar literature and the difference of this study
- Addition of a box or section on types of CO_2 sources (fossil, biogenic, DAC) and associated implications
- Clarification of the mitigation potential values included in the report (highlighting boundaries/scope of assessment more obviously)
- Explanation of the limitations of the study regarding comparative mitigation assessment

Conclusions

This study has evaluated a variety of CCU routes across materials, chemicals, fuels, and polymers to explore the strengths and weaknesses. The techniques for CO_2 utilisation varied, with some routes incorporating the entire molecule as a carbonate within polymers or building materials and others removing one or both oxygen atoms to transform CO_2 into a higher energy building block for fuels or chemicals. The scientific basis of these routes is mostly well-understood, although research is ongoing to optimise efficiencies, yields and to test suitability for new end-uses. In most cases there is also a strong knowledge of how the routes could feasibly be deployed at industrial scale, with prototypes developed and large-scale demonstrations planned or ongoing. Despite these factors, the level of further commercial development was variable and market interest uncertain. Several routes are currently not cost-competitive with conventional fossil-based production and therefore uptake is dependent on external drivers, such as carbon pricing or product mandates. Figure 3 illustrates the results of the comparative assessment of CCU commodities, using scores for each of the primary criteria to plot each (fully assessed) commodity.

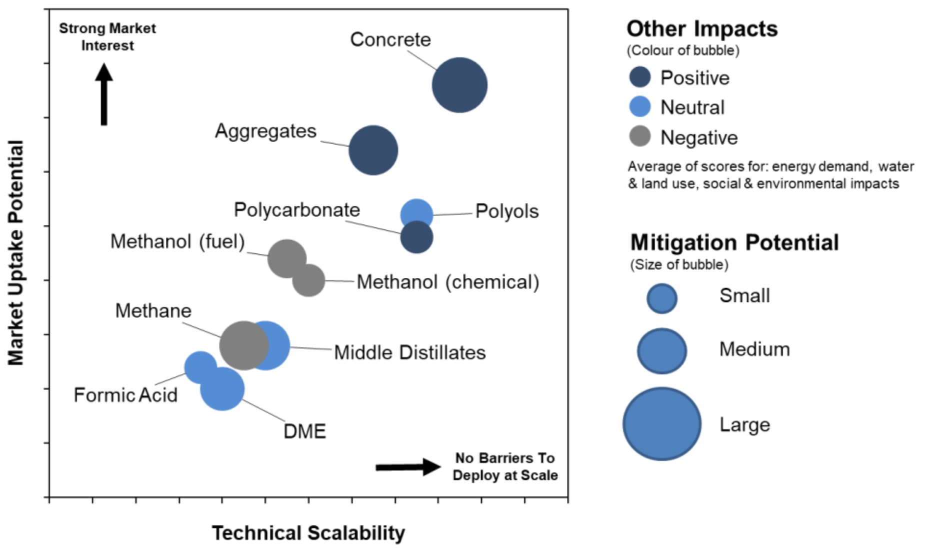


Figure 3 Summary of the comparative assessment outcome, highlighting the strengths and weaknesses of each commodity. Note that the relative position and size of bubbles represents the scoring performance, rather than absolute factors.

Almost all the CO_2 utilisation opportunities considered showed potential for lower life cycle emissions per tonne of product compared to a counterfactual. The potential scale for deployment was however much greater for fuels and building materials than for chemicals and polymers, which typically had existing markets orders of magnitude smaller. For fuels, annual abatement levels greater than 1 Gt CO_2-eq could be achieved for direct replacement ‘drop-in’ fuels due to the substitution of ‘new’ fossil carbon with captured (‘recycled’) carbon. For building materials, annual abatement levels greater than 100 Mt CO_2-eq could be achieved, through enabling a reduction in the use of emission-intensive cement and/or via permanent sequestration of CO_2. CCU building materials also have potential to offer negative emissions when CO_2 is sourced from DAC. With the exception of methanol, the total mitigation potential of polymers and chemicals was limited to below 20 Mt CO_2-eq per year.

In most cases, CO_2 utilisation routes within the chemicals and fuels categories were found to be considerably more expensive than conventional fossil-based production routes. This largely resulted from high energy requirements for the necessary green hydrogen feedstock, but also from the low yields and high catalyst costs of some of the lesser developed routes. Within the chemicals sector, the limited market drivers for CCU are unlikely to be sufficient justification for the considerable cost premium currently incurred. Within the fuels sector there is greater political and regulatory support for sustainable products, with some regions introducing mandates or standards for the use of sustainable fuels. This could increase uptake of CCU fuels for those regions, provided the benefits of synthetic CCU fuels are recognized within the regulations.

The routes considered within building materials and polymers categories were found to have greater potential under existing market drivers. In these categories the CCU opportunities offered additional value propositions, such as cost savings or enhanced properties, and in some cases have already been adopted in commercial settings. For building materials, CCU can offer cost reductions by lowering cement consumption or through the re-purposing of waste residues and avoidance of gate fees for waste disposal. For concrete, it may offer improved properties or production efficiencies. For polymers, raw material costs may be lower than the conventional route and energy requirements could decrease.

Many routes have been demonstrated at an industrially relevant scale, and in the cases of CO_2-cured concrete, waste-to-aggregates, methanol, and polycarbonates technologies were ready for commercial deployment. However, a key technical barrier for large-scale deployment of CCU fuels and chemicals could be the availability of low-carbon electricity for green hydrogen generation. For building materials, potential constraints include the distributed nature of concrete production, access to waste residues for the waste-to-aggregates route, and regulatory approval for final products. For polymers, no significant barriers to production were identified, however non-identical products must be tested, validated and approved for their suitability for specific end-uses.

There are a range of potential co-benefits for CCU routes but there can also be trade-offs. For building materials there are benefits associated with the re-use of waste residues and reductions in quarrying for raw materials. For chemicals and fuels, there are benefits from lower fossil resource consumption but trade-offs with high energy demands, additional land-use for renewables deployment and water consumption for electrolysis. Some polymer and chemical routes may offer a safer production process, avoiding toxic reagents or waste products, and synthetic fuels could be cleaner burning than counterfactuals. Additional benefits include the ability to continue using existing assets, as well as potential for energy storage applications for Power-to-X routes.

The development, deployment and uptake of CCU routes may be more favourable in: (i) regions with low-cost renewables or extensive availability of renewable energy (fuels, chemicals); (ii) regions with high cost or lack of available fossil resources (fuels, chemicals, polymers); or (iii) regions with significant low-carbon ambition coupled with political or regulatory mechanisms to incentivise CCU developments and CCU uptake (all routes). The current distribution of CCU research and development projects is concentrated mostly in the EU (44%) and the US (33%), showing that the combination of the above mentioned three factors seems most beneficial in these regions.

CO_2 utilisation opportunities are diverse, and each route has its own specific drivers, barriers, and enablers. There are, however, some common themes that span across many of the CCU routes assessed. These can be categorised into those relating to regulatory or policy factors, those relating to technical factors, and those relating to market or economic factors, including product competitiveness and market perceptions. Regulations such as mandates or standards could act as drivers for the uptake of CCU products, however prescriptive requirements may be a barrier. CCU can be facilitated through financial provisions, or through policies that level the field by recognising sustainability benefits. Drivers for CCU developments may be environmental, or they may be oriented around improving production processes or creating an enhanced product. Energy availability may be a challenge for deployment in some regions. The approvals process may act as a barrier for some products. The cost of CCU routes can be a key barrier to their adoption. However, a select few routes are driven by cost-savings or improving the value of products. A lack of awareness or engagement with product life cycle emissions and/or a lack of awareness of CCU can act as a barrier.

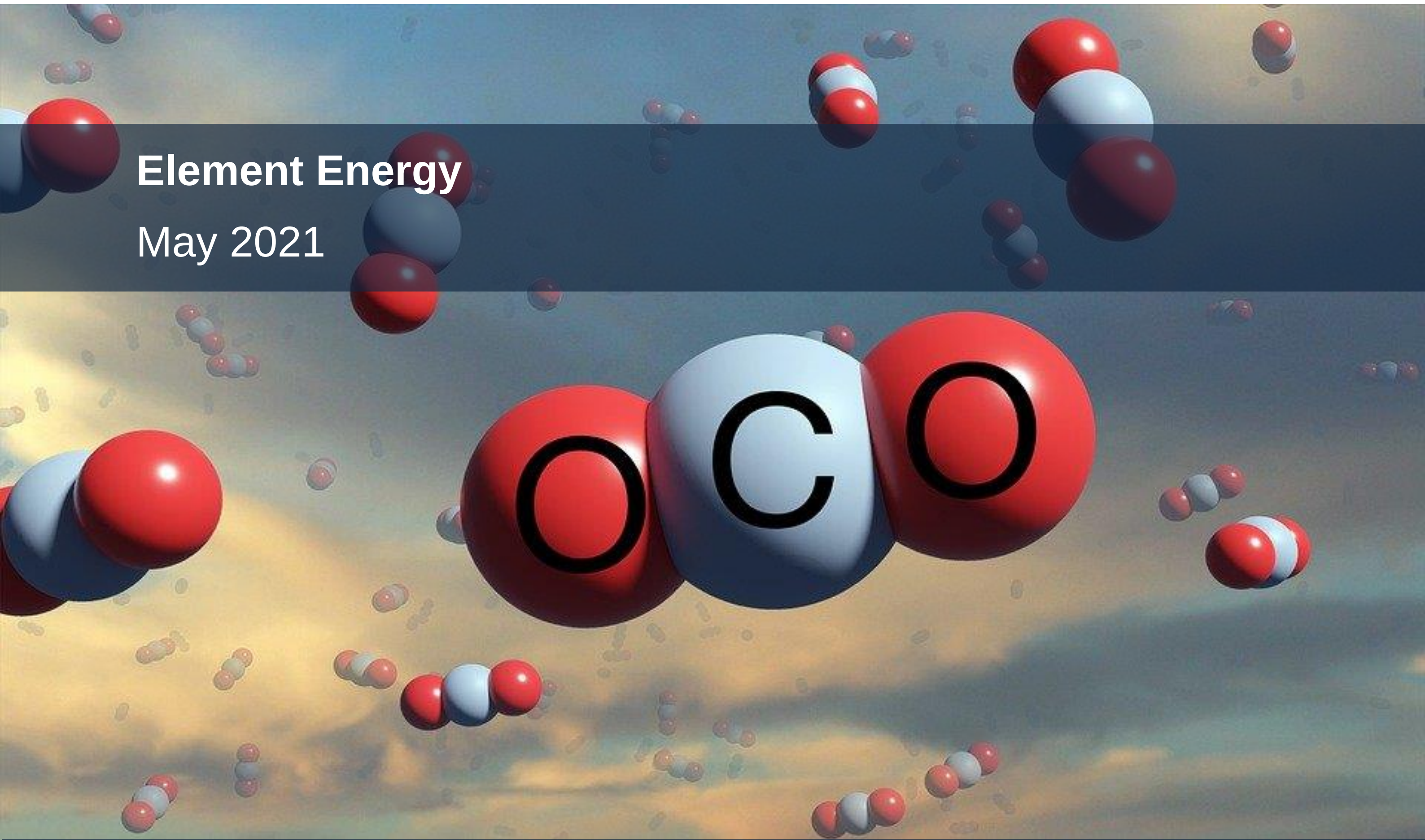
Recommendations

The following recommendations for enabling use of CO_2 as a feedstock were identified during the study:

- Researchers should focus on ensuring routes are practical to implement at scale. They should report sufficient data to allow for LCA and TEA. Subsequent analysis should follow guidelines to help with alignment of methodology and comprehension of results.
- Further work is needed to highlight priority areas for CCU development, with a particular emphasis on identifying end-uses where CCU is expected to be a favourable component of future decarbonisation pathways relative to alternative decarbonisation options.
- Researchers, institutions, and manufacturers can work to improve awareness of life cycle emissions for existing products, engage with the public and with policy makers, and improve understanding of the benefits and limitations of CCU routes.
- Industries should increase their own awareness of upstream emissions in their supply chains and identify opportunities to switch to more sustainable production routes. Knowledge sharing of information and best practise should be facilitated between similar industries.
- Policy makers can work to enable CCU by introducing support mechanisms that allow CCU to receive recognition for sustainability benefits and compete on a more level-playing field with conventional products.
- Policy makers and regulators should ensure that CCU products are incorporated appropriately into existing support schemes, regulations, and product standards. For example, by moving to performance-based standards rather than prescriptive requirements.
- Governments can encourage innovations and developments in CCU by providing funding for research programmes and demonstration projects, or through other support mechanisms.
- Further work is needed to develop, clarify and agree international frameworks for the carbon accounting of CCU routes (some of which are addressed in 2018-TR01a-c 'GHG accounting for CCU technologies', 2019-TR03 'Integrated GHG accounting guidelines for CCUS', and 2021-TR04 'CCU as a contribution to national climate change mitigation goals: Japan case study').

CO_2 as a Feedstock: Comparison of CCU Pathways

A report for



Element Energy

May 2021

Element Energy Limited, Suite 1, Bishop Bateman Court, Thompson's Lane, Cambridge, CB5 8AQ, Tel: +44 (0)1223 852499

Authors

This report has been prepared by Element Energy, with support from the Styring Group at The University of Sheffield.

Element Energy is a strategic energy consultancy, specialising in the intelligent analysis of low carbon energy. The team of over 70 specialists provides consultancy services across a wide range of sectors, including the built environment, hydrogen, 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.

Authors (Element Energy):

Antonia Mattos	Principal Consultant
Amelia Mitchell	Consultant

Supporting authors: Peter Styring, Stephen McCord, Peter Sanderson, and Guillermo Garcia-Garcia (Styring Group at The University of Sheffield), Emrah Durusut (Element Energy).

For comments or queries please contact: ccusindustry@element-energy.co.uk

Acknowledgements

We would also like to convey our thanks to the following individuals for valuable input to the study:

Jasmin Kemper	IEAGHG
Niels Berghout	IEA
Stanislas Van den Berg	Total
David Nevicato	Total
Kai Hortman	Total
Aicha El Khamlichi	Ademe
Volker Sick	Global CO_2 Initiative
Christian von Olshausen	Sunfire
Rebecca Boudreaux	Oberon Fuels
Alistair Sanderson	Unilever
Paula Carey	Carbon8 Systems
Benedikt Stefansson	Carbon Recycling International
Marcius Extavour	Carbon XPrize

Front cover image from Pixabay.

Disclaimer

This study was developed in parallel with '**CO_2 Reality Check: Hydrogenation**', which provides a more detailed look at factors impacting the mitigation potential, costs, and energy demands of methanol, middle distillate hydrocarbons, and formic acid. This parallel study also highlights implications of some of the CO_2 accounting challenges and discusses additional motivations for CCU. Many readers may find it useful to read the studies together to provide complementary information and perspectives.

Executive summary

Everyday products contain carbon atoms. These carbon atoms typically come from fossil resources, but they could also come from CO_2 captured directly from industrial flue gases, from biogenic CO_2 sources or from the air. The use of captured CO_2 to make value-added products is known as carbon capture and utilisation (CCU). There is increasing interest in the chemical transformation of CO_2 to value-added products, such as building materials, chemicals, polymers, and synthetic fuels. This is driven partly by goals to increase sustainability, lower emissions, and move towards more circular production routes. Developments have also been driven by realisations that producing some products using CO_2 as a feedstock could lead to improvements in the product or the process, such as enhanced properties or lower feedstock costs.

This study investigates CO_2 utilisation opportunities that allow CO_2 to be used as a feedstock in the production of building materials, chemicals, polymers, and fuels. Strengths and weaknesses for individual opportunities are identified through a comparative assessment approach in which routes are scored for four primary criteria:

CO_2 mitigation potential

Evaluates: The ability of the CCU route to lead to emissions abatement in the future if there are no technology or economic barriers.

Considers: The emissions avoided compared to a conventional route and the maximum possible deployment based on the addressable market size.

Market uptake potential

Evaluates: The ability of the CCU route to have an established future market in a low-carbon world, if there are no technology barriers.

Considers: Drivers for the uptake of the product, the existing commercial development of the route, and any barriers limiting market interest.

Technical scalability

Evaluates: The ability of the CCU route to deploy globally or at a large scale, if there is significant market demand.

Considers: Technology readiness level, ease-of-deployment, and factors that may constrain the scale of deployment, such as high energy demands.

Other impacts

Evaluates: The extent of additional impacts that would occur through deployment of the CCU route.

Considers: Consumption of energy, water and land compared to the conventional route, and other social or environmental factors.

A total of 12 CO_2 utilisation opportunities were investigated across the four categories. These were selected to demonstrate a wide range of applications with a variety of benefits and trade-offs.

Category	Commodity	Market Size*	Utilisation Method(s)
Building Materials	Concrete	30 Gt	Forming mineral carbonates
	Aggregates - Manufactured	1 Gt	Forming mineral carbonates
Chemicals	Methanol - Chemical Intermediate	80 Mt	Hydrogenation
	Formic Acid	1 Mt	Hydrogenation / Electrochemical reduction
	Dimethyl Carbonate (DMC)	90 kt	Reacting CO_2 and epoxides / Reacting CO_2 and methanol
Polymers	Polycarbonate	4 Mt	Reacting CO_2 and epoxides
	Polyols for Polyurethane	12 Mt	Reacting CO_2 and epoxides (catalytic co-polymerisation)
Fuels	Middle Distillate Hydrocarbons	3 Gt	Hydrogenation
	Synthetic Methane	2 Gt	Hydrogenation
	Dimethyl Ether (DME)	500 Mt	Hydrogenation
	Ethanol	100 Mt	Electrochemical reduction
	Methanol - Gasoline Blending	30 – 170 Mt	Hydrogenation

* Market size indicates the 2019/2020 production of conventional product (in units of tonnes of product) to provide an indication of scale

Comparative Assessment Outcomes

Building materials and fuels have a greater total mitigation potential than polymers and chemicals due to the larger market size of commodities. Almost all the CO_2 utilisation opportunities considered showed potential for lower lifecycle emissions per tonne of product compared to a counterfactual. The potential scale for deployment was however much greater for fuels and building materials than for chemicals and polymers, which typically had existing markets orders of magnitude smaller. For fuels, annual abatement levels greater than 1 Gt CO_2-eq could be achieved for direct replacement 'drop-in' fuels due to the substitution of 'new' fossil carbon with captured ('recycled') carbon. For building materials, annual abatement levels greater than 100 Mt CO_2-eq could be achieved, through enabling a reduction in the use of emission-intensive cement and/or via permanent sequestration of CO_2. CCU building materials also have potential to offer negative emissions. With the exception of methanol, the total mitigation potential of polymers and chemicals was limited to below 20 Mt CO_2-eq per year.

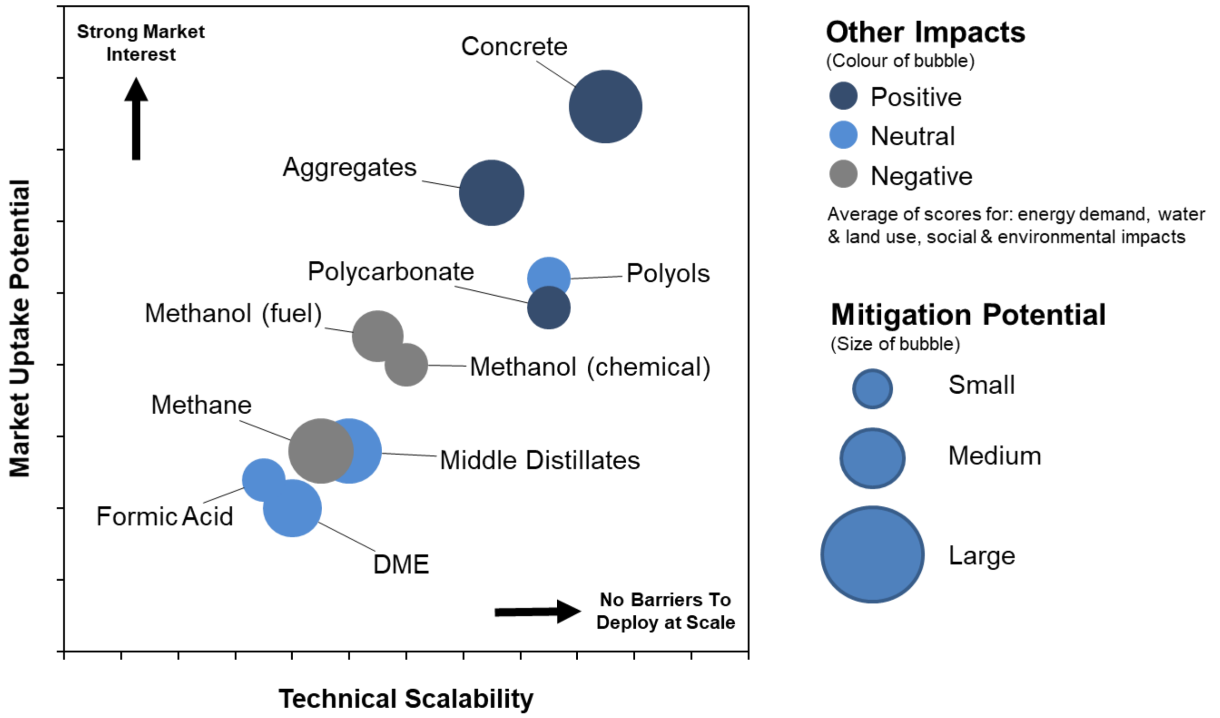
For fuels and chemicals, current market drivers for CCU are typically not sufficient to incentivise large scale market uptake. In most cases, CO_2 utilisation routes within the chemicals and fuels categories were found to be considerably more expensive than conventional fossil-based production routes. This largely resulted from high energy requirements for the necessary green hydrogen feedstock, but also from the low yields and high catalyst costs of some of the lesser developed routes. Within the chemicals sector, the limited market drivers for CCU are unlikely to be sufficient justification for the considerable cost premium currently incurred. Within the fuels sector there is greater political and regulatory support for sustainable products, with some regions introducing mandates or standards for the use of sustainable fuels. This could increase uptake of CCU fuels for those regions, provided the benefits of synthetic CCU fuels are recognized within the regulations.

The routes considered within building material and polymer categories were found to have greater market uptake potential under existing drivers. In these categories the CCU opportunities offered additional value propositions, such as cost savings or enhanced properties, and in some cases have already be adopted in commercial settings. For building materials, CCU can offer cost reductions by lowering cement consumption or through the re-purposing of waste residues and avoidance of gate fees for waste disposal. For concrete, it may offer improved properties or production efficiencies. For polymers, raw material costs may be lower than the conventional route and energy requirements could decrease.

Many routes are technically well-developed but deployment factors could constrain global scale-up. In the majority of cases, the technologies for CO_2 utilisation have been proven in a relevant environment or were expected to be composed of technologies that have been proven individually. Many routes had been demonstrated at an industrially relevant scale, and in the cases of CO_2-cured concrete, waste-to-aggregates, methanol, and polycarbonates technologies were ready for commercial deployment. However, a key technical barrier for large-scale deployment of CCU fuels and chemicals could be the availability of low-carbon electricity for green hydrogen generation. For building materials, potential constraints include the distributed nature of concrete production, access to waste residues for the waste-to-aggregates route, and regulatory approval for final products. For polymers, no significant barriers to production were identified, however non-identical products must be tested, validated, and approved for their suitability for specific end-uses.

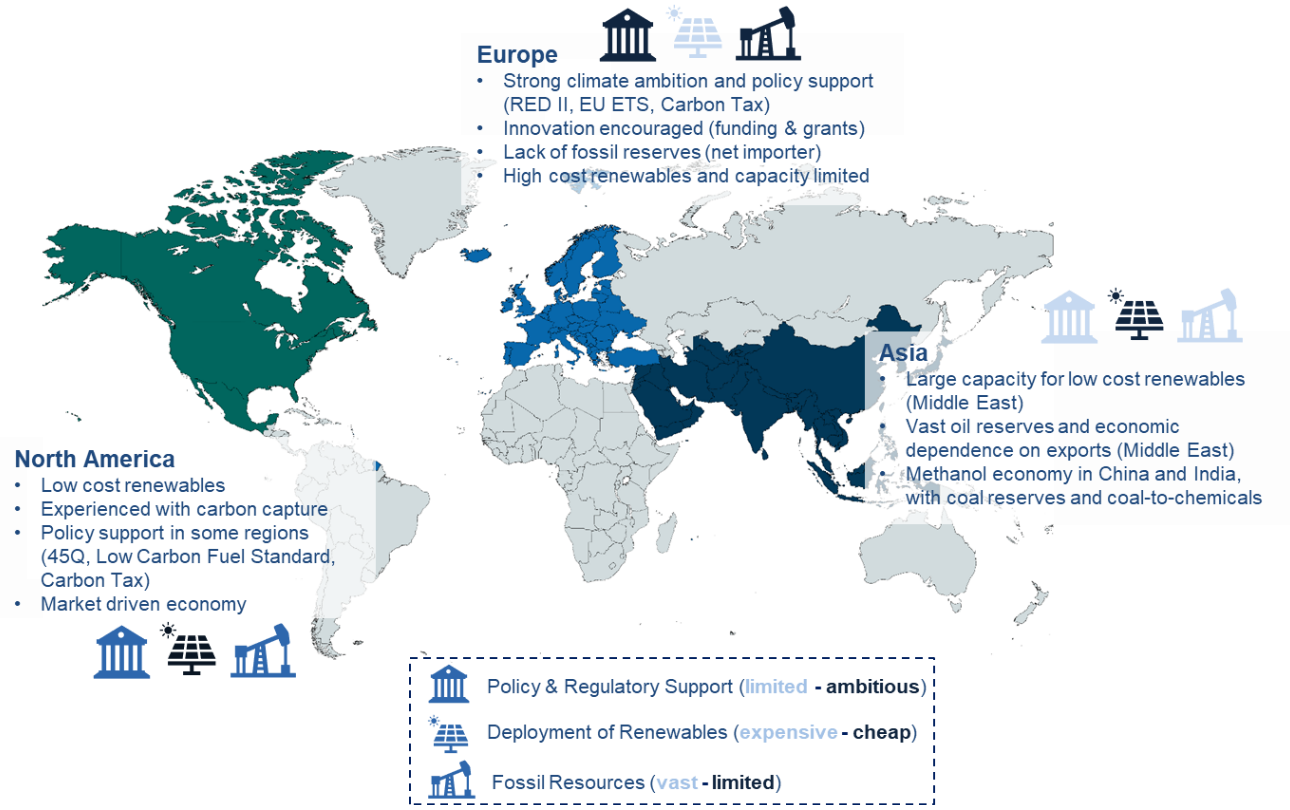
There are a range of potential co-benefits for CCU routes but there can also be trade-offs. For building materials there are benefits associated with the re-use of waste residues and reductions in quarrying for raw materials. For chemicals and fuels, there are benefits from lower fossil resource consumption but trade-offs with high energy demands, additional land-use for renewables deployment and water consumption for electrolysis. Some polymer and chemical routes may offer a safer production process, avoiding toxic reagents or waste products, and synthetic fuels could be cleaner burning than counterfactuals. Additional benefits include the ability to continue using existing assets, as well as potential for energy storage applications for Power-to-X routes.

Each of the commodities investigated was given an individual score for the four criteria assessed, with a summary of the results displayed below, highlighting the strengths and weaknesses of each commodity. Note that the position and size of bubbles represents the relative scoring performance, rather than directly correlating to absolute factors, such as market size.



Regional Considerations

The future success of CCU technologies will be influenced by a variety of factors, many of which can vary significantly between countries and/or regions. Three factors that could impact the success of multiple CCU routes are fossil resources (availability / dependence), deployment of renewable electricity generation, and policy & regulatory support.



Fossil resources: The availability of fossil resources impacts the cost of producing conventional fossil-based chemicals, polymers, and fuels as these are typically derived from fossil-feedstocks. High conventional prices could enable CCU products to be more competitive. Importers of fossil resources, such as Europe, may be concerned about security of supply, acting as a driver for more local CCU production pathways.

Deployment of renewables: Many of the chemical and fuel CCU routes use hydrogen produced from electrolysis, meaning that costs are highly dependent upon the cost of renewable electricity. The ability to deploy renewables and the cost of these renewables is therefore an influencing factor for the uptake of relevant CCU routes. Currently solar photovoltaic costs are lowest in North America and the Middle East. Regions where there is limited opportunity for renewables installations may choose to prioritise the use of these renewables for other decarbonisation routes.

Policy & regulatory support: CCU routes that are not cost competitive with conventional products are likely to require significant policy or regulatory support to achieve market uptake. Provision of early funding support also enables development of innovative technologies and the deployment of demonstration projects. Support for CCU is more likely to be available in regions with strong climate ambitions. For example, the European Union has the Renewable Energy Directive (RED II), an Emissions Trading System (ETS), and many countries have imposed additional carbon taxes such as Sweden (USD 119 / t CO_2) and Switzerland (USD 99 / t CO_2)[1].

The development, deployment and uptake of CCU routes may be more favourable in: regions with low-cost renewables or extensive availability of renewable energy (fuels, chemicals); regions with high cost or lack of available fossil resources (fuels, chemicals, polymers); or regions with significant low-carbon ambition coupled with political or regulatory mechanisms to incentivise CCU developments and CCU uptake (all routes).

[1] World Bank Group 2020, State and Trends of Carbon Pricing 2020 [LINK]

According to analysis of the SCOT database, the current distribution of CCU research and development projects is concentrated mostly in the EU (44% of projects) and the US (33% of projects)[2].

Drivers, Barriers and Enablers

CO_2 utilisation opportunities are diverse, and each route has its own specific drivers, barriers, and enablers. There are, however, some common themes that span across many of the CCU routes assessed. These can be categorised into those relating to regulatory or policy factors, those relating to technical factors, and those relating to market or economic factors, including product competitiveness and market perceptions.

Regulatory and Policy

Regulations such as mandates or standards could act as drivers for the uptake of CCU products, however prescriptive requirements may be a barrier. The introduction of legal requirements for manufacturers or firms to supply or procure a minimum percentage of products from sustainable or low-emission sources can have the impact of increasing demand for these products, offering CCU routes a more viable route to market and fostering innovations. However, the use of prescriptive requirements can inadvertently exclude CCU products, making performance-based regulations preferable. Existing regulations may need to be updated to enable some CCU routes, for example aggregates from waste must be recognised as ‘end-of-waste’ before use, and increases in blending limits could benefit synthetic fuels.

CCU can be facilitated through financial provisions, or through policies that level the field by recognising sustainability benefits. As with many emerging technologies, the development, demonstration, and uptake of CCU technologies can be facilitated by financial support from governments or institutions. The cost premium of CCU products is currently a barrier for many routes. Policies that allow CCU products to realise value from their sustainability benefits would enable CCU products to be more competitive in the market. For example, carbon pricing mechanisms, such as a carbon tax or emissions trading scheme, or other policy support schemes such as a Contract for Difference style mechanism. Further clarity is needed on how benefits may be realised through carbon accounting.

Technical

Drivers for CCU developments may be environmental, or they may be oriented around improving production processes or creating an enhanced product. Factors such as emission avoidance, the recycling of CO_2, circular economy principles and the avoidance of fossil feedstocks are often cited as motivations for developing CCU routes. There are also examples in which CCU was adopted partially because the production route was superior to existing processes, or because the route produces products that offer enhanced properties compared with conventional products.

Energy availability may be a challenge for deployment in some regions. The CCU routes with high energy demands may face barriers obtaining low-emission intensity electricity, with dedicated renewables likely required to avoid impacting the wider energy system. Deployment of or access to large capacities of renewables for CCU may prove challenging in some regions where costs are high or where there is high competition for renewables.

The approvals process may act as a barrier for some products. Market uptake of CCU products may be reliant on products meeting regulatory requirements or standards, and potentially undergoing lengthy and expensive approvals processes. This may present technical challenges, for example the need to produce large volumes of aviation fuels for testing, the need to meet highly prescriptive criteria, or a lack of available testing facilities. New products will need to demonstrate their suitability for the intended applications before they can be deemed acceptable by industry, with conservative nature of some markets presenting additional barriers.

[2] IEAGHG 2018, Accounting for CO_2 Capture and Utilisation (CCU) Technologies – 2018 TR01c [LINK]

Market and Economic

The cost of CCU routes can be a key barrier to their adoption. However, a select few routes are driven by cost-savings or improving the value of products. CCU routes for chemicals and fuels currently have much higher production costs than their counterfactuals, acting as a significant barrier to market uptake. There is an opportunity for carbon pricing mechanisms to lower cost premiums, however to achieve cost-parity much more ambitious carbon prices are needed than those currently adopted. Alternatively, market uptake of sustainable products could be driven by a need to comply with imposed targets or regulations. Some CCU routes in building materials and polymers already have a business case in certain regions without additional policy or regulatory support.

A lack of awareness or engagement with product lifecycle emissions and/or a lack of awareness of CCU can act as a barrier. Manufacturers can lack awareness of emissions in their supply chains or product end-uses. They may not consider themselves responsible for these indirect (Scope 3) emissions or may not be able to accurately obtain data on them[148]. Furthermore, the lack of commercial development, clarity, and marketing of CCU may mean that engaged companies do not consider CCU products in decarbonisation plans. Consumer perception is also important, with limited evidence on the impact. The concept of CCU may be perceived negatively by consumers, who may have concerns about the use of CO_2 in products. On the other hand, careful marketing could allow products to use sustainability as a selling point.

Recommendations

Recommendations to enable improved understanding, further development, and facilitate uptake of appropriate CO_2 utilisation opportunities include:

- Researchers should focus on ensuring routes are practical to implement at scale. They should report sufficient data to allow for life-cycle and techno-economic analysis. Subsequent analysis should follow guidelines to help with alignment of methodology and comprehension of results.
- Further work is needed to highlight priority areas for CCU development, with a particular emphasis on identifying end-uses where CCU is a favourable component of future decarbonisation pathways relative to alternative decarbonisation options.
- Researchers, institutions, and manufacturers can work to improve awareness of lifecycle emissions for existing products, engage with the public and with policy makers, and improve understanding of the benefits and limitations of CCU routes.
- Industries should increase their own awareness of upstream emissions in their supply chains and identify opportunities to switch to more sustainable production routes. Knowledge sharing of information and best practise should be facilitated between similar industries.
- Policy makers can work to enable CCU by introducing support mechanisms that allow CCU to receive recognition for sustainability benefits and compete on a more level-playing field with conventional products.
- Policy makers and regulators should ensure that CCU products are incorporated appropriately into existing support schemes, regulations, and product standards. For example, by moving to performance-based standards rather than prescriptive requirements.
- Governments can encourage innovations and developments in CCU by providing funding for research programmes and demonstration projects, or through other support mechanisms.
- Further work is needed to develop, clarify and agree international frameworks for the carbon accounting of CCU routes.

Acronyms

ATR	Autothermal Reforming
BREEAM	BRE's Environmental Assessment Method
BPA-PC	Bisphenol-A-based polycarbonates
CAPEX	Capital Expenditure
CCS	Carbon Capture and Storage
CCU	Carbon Capture and Utilisation
CCUS	Carbon Capture, Utilisation, and Storage
CO_2	Carbon Dioxide
CO_{2e}	Carbon Dioxide Equivalents
CRI	Carbon Recycling International
DMC	Dimethyl Carbonate
DME	Dimethyl Ether
EOR	Enhanced Oil Recovery
ETS	Emissions Trading System
EU	European Union
FOAK	First-of-a-Kind
F-T	Fischer–Tropsch
GHG	Greenhouse Gas
H_2	Hydrogen
LCA	Life Cycle Assessment
Mt	Mega tonne
MTBE	Methyl tert-butyl ether
NG	Natural Gas
PUR	Polyurethane
PtX	Power-to-X
PV	Photovoltaics
RD&D	Research, Development & Demonstration
RED	Renewable Energy Directive
rWGS	Reverse Water Gas Shift
SMR	Steam Methane Reformation
TRL	Technology Readiness Level
T&S	Transport and Storage

Contents

1 Context

1.1 Introduction

Everyday products contain carbon atoms. The vast majority of plastics are made up of polymer chains that are mostly carbon atoms by weight, with the most common plastics of polyethylene and polypropylene being 86% carbon by weight. A large amount of chemicals contain carbon atoms, including olefins such as ethylene, aromatics such as benzene and alcohols such as methanol. These chemicals are used industrially in manufacturing as solvents or chemical intermediates, but also are key components of everyday items such as cleaning products, personal hygiene products, paints, and adhesives. Fuels such as diesel, gasoline and kerosene are composed of hydrocarbons that are on average 86% carbon by weight. Carbon is contained within biological materials, including plants, foods, and natural fibres. It is also contained within natural mineral products, such as rocks, which are feedstocks for building materials such as concrete.

At the end of a products lifetime these carbon atoms often end up in the atmosphere, contributing to global warming. Fuel products may last for less than a year, chemicals less than 10 years, and polymers less than 100 years. At the end of the products life, such as on combustion of fuels, incineration of wastes or natural degradation, the carbon atoms contained within these products often enter the atmosphere as carbon dioxide (CO_2), with exceptions where this carbon is captured and stored. Conversely carbon in building materials can adopt a stable form that is unlikely to enter the atmosphere under normal conditions. There is robust evidence to suggest that the increase of greenhouse gases such as carbon dioxide in the atmosphere leads to global warming. Countries have pledged to cut their CO_2 emissions with the aim of keeping global warming well-below a 2°C rise compared to pre-industrial levels.

Carbon atoms could come from fossil resources, but they could also come directly from the air or from industrial flue gases or biogenic sources. Typically, the carbon contained within today's chemicals, polymers and fuels has been derived from fossil resources, meaning that any emission results in increased concentrations of CO_2 as carbon is removed from geological deposits and enters the atmosphere. Alternatively, carbon could be sourced from the atmosphere in the first place, **offering a circular carbon solution** in which CO_2 is emitted and then re-used in a best-case net-neutral emission system. The capture of atmospheric CO_2 occurs naturally in the growth of plants (biogenic CO_2) but can also be achieved through engineered removals, such as direct air capture (DAC) technologies. An intermediate option is to source carbon from industrial flue gases that would otherwise be emitted. Although this carbon may have originated from the combustion of fossil fuels, this approach allows the re-use of the carbon before it is emitted.

Carbon capture & utilisation (CCU)

CO_2 utilisation is the use of CO_2 at above atmospheric concentrations to produce valuable products, either through direct use as CO_2 (e.g. carbonated drinks) or through chemical or biological conversion (e.g. to carbon-based chemicals, fuels). CO_2 is already used extensively for urea manufacture in the fertiliser industry, for enhanced oil recovery (EOR), and for food and beverage production, with other conventional applications including use in fire-extinguishers, greenhouses, and cooling systems. **Carbon capture & utilisation (CCU)** refers to CO_2 utilisation in which the supplied CO_2 is captured either from an emission point source (e.g. fossil fuel combustion in an industrial plant) or directly from the atmosphere.

Carbon capture technologies have been deployed across the world. A range of carbon capture technologies have been developed, including amine-based routes and calcium looping methods, some of which are now considered to be at technology readiness level (TRL) 9. These technologies have been deployed across the world in large-scale CCUS projects, which in 2020 had a capture and storage capacity of 40 Mt CO_2 per year[3]. Initial projects captured CO_2 from the high concentration emissions of natural gas processing and fertiliser plants but projects are expanding to encompass capture from areas such as power

[3] GCCSI 2020, Global Status of CCS 2020 [LINK]

generation and iron & steel production[3]. Direct air capture technologies, capable of capturing CO_2 directly from the atmosphere, have recently been developed and demonstrated.

There is **increasing interest in the chemical transformation of captured** CO_2 to value-added products, such as building materials, chemicals, polymers, and synthetic fuels. This is driven partly by goals to increase sustainability, lower emissions, and move towards more circular production routes. Developments have also been driven by realisations that producing some products using CO_2 as a feedstock could lead to improvements in the product or the process, such as enhanced properties or lower feedstock costs.

CCU for emission mitigation

Carbon capture and storage (CCS) is acknowledged to be a vital technology for meeting global climate targets in a cost-effective manner. CCS has numerous applications across a low-carbon energy system; it can help decarbonise power generation and energy intensive industries, as well as indirectly facilitate emissions reductions in heat and transport, when used for hydrogen production. On average across IPCC 1.5 Degrees Scenarios (1.5DS) there are 13 $GtCO_2$ captured annually by 2060 and the IEA estimates that with limited CO_2 storage (and hence CCS), the decarbonisation cost could be $4 trillion greater globally[4]. **CCU can be complementary to CCS.** With large volumes of CO_2 projected to be captured in the longer term, CCU and CCS can play complementary roles in climate change mitigation.

For many utilisation routes, CO_2 **sequestration is only temporary** with utilised CO_2 being emitted to the atmosphere as the product is combusted or degrades at its end-of-life. In absolute terms, these CCU routes are therefore at-best carbon neutral but typically net-positive in emissions when their entire lifecycle is considered. Benefits however lie in the **avoidance of alternative more emission intensive feedstocks** or production processes. Many chemicals, polymers and fuels are made up of carbon atoms that would usually be derived from emission-intensive fossil feedstocks. The utilisation of CO_2 offers an alternative source of carbon atoms, and can offer a lower-emission production pathway to producing the same commodity. In this way CO_2 emissions are avoided.

However, for some routes CO_2 sequestration is considered permanent. For utilisation routes that convert CO_2 to a more stable form, such as a mineral carbonate, the CO_2 can be considered permanently sequestered as it is unlikely to encounter the conditions that would be needed unlock it from this stable form. These routes therefore offer a way to store captured CO_2.

1.2 Origins of CO_2 feedstock

This study focuses on investigating products that can made from CO_2 as a feedstock, without explicitly considering the origin of the CO_2 feedstock. However, the origin of the CO_2 feedstock for utilisation pathways has important implications for mitigation potential and costs, as well as wider factors such as energy consumption, societal acceptance, and scale or location of deployment. A key consideration for CCU mitigation assessment is the counterfactual of what would otherwise happen if the CO_2 were not utilised. This may differ depending on the origin of the CO_2. Furthermore, the cost of CO_2 capture is dependent upon many factors including the concentration and purity of the source. The supply cost of this CO_2 to the utilisation pathway may also be impacted by various business dynamics, such as carbon pricing and attractiveness of alternative CO_2 destinations. Some of these considerations are outlined below for different categories of CO_2 origin, with the intention of providing a brief overview as further context for this study.

Industrial CO_2 (non-biogenic)

CO_2 emissions can result from fuel combustion (fossil or biogenic origin) or process emissions at industrial sites. A range of technologies have been developed to capture industrial CO_2 emissions from concentrated streams or diluted flue gases, such as amine-based routes and calcium looping methods. In 2019 there were 51 large scale operational CCUS projects using industrial carbon capture technology[3].The cost of capture is dependent upon the size of the capture plant and the partial pressure of CO_2 in the flue gas, with examples

[4] The Role of CO_2 Storage, IEA 2019 LINK

ranging from USD 10-300 per tonne of CO_2 captured[5]. Energy demand also varies with the type of CO_2 source, with lower concentration and lower purity gas streams requiring a higher energy input. Capture from an iron-and-steel plant (concentration - 17-35%) requires approximately 200 kWh of electricity and 1 GJ thermal energy[6].

Industrial emitters may have various solutions that could avoid fossil-CO_2 emissions, such as permanent storage of captured CO_2 or elimination of CO_2 emissions through fuel-switching or process change. The utilisation of CO_2 from fossil origin can avoid the immediate emission of this CO_2 from the industrial source, however many CCU pathways do not provide a permanent store for CO_2. Therefore, in these cases the fossil CO_2 is eventually still emitted to the atmosphere, meaning that the lifecycle has positive CO_2 emissions. Climate benefits may however be realised if the CCU product substitutes a conventional product that would also emit fossil CO_2 at its end-of-life (such as a fossil fuel). In this case, the industrial fossil emissions are 'recycled' and the conventional end-of-life emissions are avoided.

Biogenic CO_2

Industrial emitters may emit CO_2 of biogenic origin – for example, during bioethanol processing (fermentation), biomass gasification, or combustion of biomass. The capture of this CO_2 is the same as described for industrial capture above. The gas stream from bioethanol processing has a high concentration of CO_2, allowing for cheaper and lower energy capture: capture costs are estimated at approximately USD 10 per tonne of CO_2, [5] with an energy requirement of approximately 100 kWh of electricity and minimal thermal energy[6].

On the assumption that biogenic CO_2 was recently atmospheric, the emission of biogenic CO_2 can be seen as the return of this CO_2 back to the atmosphere, with potential to be a net-neutral cycle. Industrial emitters may have options to capture and permanently store biogenic CO_2 emissions, allowing for net atmospheric CO_2 removal. Net removals could also occur with utilisation routes with permanent sequestration. For other CCU routes, utilisation of biogenic CO_2 may at best-case be a net-neutral cycle, if the CO_2 is released at end-of-life but no additional emissions occur. As described above for fossil CO_2, additional climate benefits may accrue due to the avoidance of fossil emissions through substitution of a conventional product.

Atmospheric CO_2

A range of technologies are being developed to capture CO_2 at atmospheric concentrations, known as direct air capture (DAC), with multiple pilot projects in existence. These include aqueous sorbent and solid sorbent processes, such as those developed by Carbon Engineering, Climeworks, and Global Thermostat[7]. The low concentration of atmospheric CO_2 means that DAC technology has higher energy requirements than industrial capture - approximately 4-6 GJ of thermal energy and 400 kWh of electrical energy per tonne of CO_2 captured[8,9]. There are a broad range of capture cost estimates reported in the literature, however developers have claimed that nth-of-a-kind plant costs could fall to USD 100 per tonne[8,9].

The capture of atmospheric CO_2 can lead to net-CO_2 removals if the CO_2 is subsequently permanently sequestered – this could be achieved via utilisation if the route offers permanent storage or alternatively via geological sequestration. For CCU routes where the CO_2 is re-emitted at the products end-of-life, there is potential for a net-neutral cycle, if no other emissions occur. As for the other CO_2 origins considered, additional climate benefits can occur if the product from CO_2 utilisation substitutes a conventional product with end-of-life fossil emissions (such as a fossil fuel). In this case, the atmospheric CO_2 is 'recycled' and the conventional end-of-life emissions are avoided.

[5] GCCSI 2021, Technology Readiness and Cost of CCS [LINK]
[6] Von der Assen et al. 2016, Selecting CO2 Sources for CO2 Utilization by Environmental-Merit-Order Curves
[7] ICEF 2018, Direct Air Capture of Carbon Dioxide [LINK]
[8] Joule 2018, A Process for Capturing CO_2 from the Atmosphere
[9] Beuttler et al 2019, The Role of Direct Air Capture in Mitigation of Anthropogenic Greenhouse Gas Emissions

1.3 Objectives, scope & additionality

This study investigates different products that could be made using a CO_2 feedstock. The focus is on the CCU product produced and how it compares to its conventional counterpart, with subsequent comparison of the different CCU products. Specially, this study investigates CO_2 utilisation opportunities that allow CO_2 to be used as a feedstock in the production of building materials, chemicals, polymers, and fuels. The intention is to present a holistic assessment of the route's feasibility (both technically and from a market perspective), the effect on CO_2 emissions and any additional impacts. The aim is to identify areas of strength and weakness within individual routes, compare different CCU pathways, identify common drivers, barriers, and enablers.

Specific objectives were to:

- Provide a comprehensive review of available literature and clearly compare different CCU pathways used to produce fuels, chemicals, polymers, and construction materials.
- Consider the strengths and weaknesses of CO_2-conversion routes, focusing on the CO_2 mitigation potential and other benefits
- Conduct independent and impartial analysis, without dismissing or promoting certain utilisation options but rather determining the potential of each CCU option.
- Identify key barriers, enablers and drivers for the deployment of CCU at scale
- Determine the RD&D, policy, and regulatory gaps required to be closed.

There are multiple past studies and literature reviews that provide insights into CO_2 utilisation opportunities, some of which are described in Table 1 below.

Table 1: Relevant existing studies that summarise a broad range of CCU opportunities.

Study	Description / Focus Area
The technological and economic prospects for CO_2 utilization and removal (Hepburn et al. 2019)	Scoping review of peer-reviewed literature covering the scale and economics of select utilisation pathways, including chemicals, polymers, fuels, building materials.
Putting CO_2 To Use (IEA, 2019)	Report summarising CCU market opportunities and assessing their potential to utilise at least 10 Mt CO_2. Includes consideration of scalability, competitiveness, climate benefits, and regulations.
Developments on CO_2-utilization technologies (IEACCC, 2019)	Reviews recent developments and status of CO_2 conversion technologies, highlighting companies and research, with some life cycle analysis and technical data extracted and presented.
Global Roadmap Study of CO2U Technologies (LuxResearch, 2018)	Categorisation of CCU technology developers and analysis of progress. Use of scenarios to estimate market penetration and addressable market size. Overview of technologies, market drivers, barriers, and enablers.
Carbon Dioxide Utilisation (CO_2U). ICEF Roadmap 2.0. (ICEF, 2017)	Overview of CCU building materials, chemicals, durable carbon materials. Includes discussion of technical, market, LCA challenges, and policy factors.
Assessing The Potential of CO_2 utilisation in the UK (ECOFYS and Imperial College London, 2017)	Considers the abatement potential of select CCU routes and provides a broad technology assessment (TRL, developers, markets, barriers, and opportunities).

The present study both consolidates and builds upon these past studies through inclusion of a broad set of insights, additional in-depth details from academic papers, and more recent technology developments. Furthermore, the present study provides additionality through the inclusion of a simple comparative framework to clearly highlight the relative strengths and weaknesses of different CCU products, based upon information available in the literature and the authors interpretations of this literature. A total of 11 different commodities are assessed in the present study covering a range of product categories and CO_2 conversion pathways. The assessment covers mitigation potential, market uptake potential, technical scalability, and other impacts.

1.4 Report structure

The report is structured into 8 chapters as follows:

Chapter 2 describes the approach to the study and the assessment methodology. It also contains relevant background information on carbon accounting and lifecycle assessments.

Chapters 3-6 contain the assessment of CO_2 utilisation in the areas of building materials (Chapter 3), chemicals (Chapter 4), polymers (Chapter 5) and fuels (Chapter 6). These chapters each include a brief introduction to the sector and products considered, followed by sections on:

- **'CO_2 utilisation pathways'** that describe utilisation opportunities in the sector with details on specific routes and the outcomes of the assessment for those routes.
- **'CCU strengths, weaknesses, and discussion'** that highlight the commonalities and differences between the routes, discuss additional factors that may influence the assessment.

Chapter 7 highlights regional differences that can have an impact on the performance of the commodities in the areas assessed, including case studies for the regions of Asia, Europe, and North America.

Chapter 8 discusses the findings, incorporating a comparison of all categories and routes assessed, identification of common drivers, barriers and enablers and concluding recommendations.

This report is also accompanied by an appendix detailing more information on the assessment criteria used.

2 Approach & Methodology

The objective of the study was to investigate the use of CO_2 as a feedstock for select commodities that fall under the categories of building materials, chemicals, polymers, and fuels. This involved conducting a holistic, comparative assessment of a broad range of CO_2 utilisation opportunities, focusing on four primary areas: mitigation potential, competitiveness & market potential, technical scalability, and other impacts. The aim was to highlight the strengths and weaknesses of using CO_2 as a feedstock for each commodity, and to identify the key drivers and enabling factors for CO_2 utilisation within these categories of commodities. The study scope included a global focus with additional commentary on regional variations.

The approach to the study is outlined in Figure 1. The initial steps involved a literature review and the selection of the commodities for assessment. A further literature review was then conducted alongside stakeholder engagements to validate findings, fill any data gaps, and gain broader input on recent developments. The next steps were to outline an approach for the comparison of the commodities (discussed below) and to conduct the comparative assessment. The results were used to identify the areas of strength and weakness for each commodity. They were also used to identify regional variations that might impact the success of the commodities within the four main assessment categories. The final task involved the identification of drivers and enabling factors, followed by recommendations on further work, RD&D, and policy support.

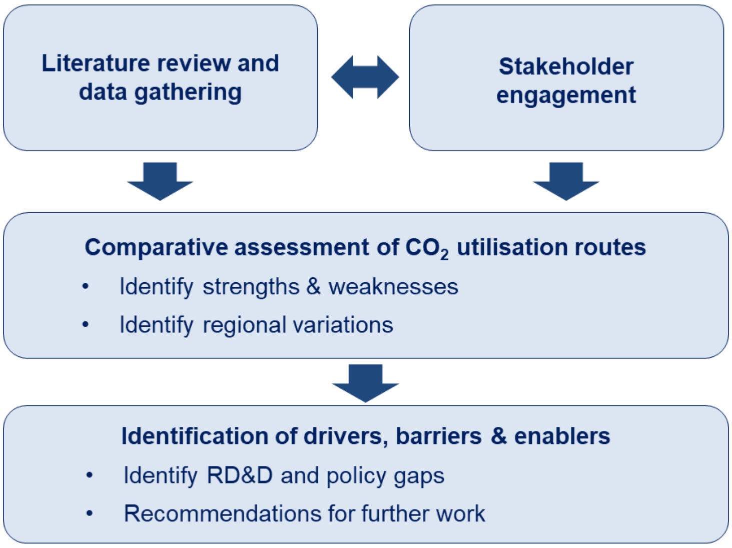


Figure 1: Outline of approach to study

2.1 Selected Commodities

Commodities were selected to highlight a broad range of CO_2 utilisation options within the defined categories, with expert consultations used to guide the selection. The commodities that were investigated within the study are outlined below (Table 2). For most of the chosen commodities, a single type of CO_2 utilisation pathway, the most developed option, was selected for assessment. In a few cases, multiple pathways were considered due to the similarity in characteristics or because the 'most developed' pathway was not easily defined. The list is not a comprehensive list of the CO_2 opportunities available.

Table 2: CO_2 Utilisation Pathways Included in Assessment

Commodity	Utilisation Method	Description
Concrete	Forming mineral carbonates	Two routes are considered: (1) utilisation of CO_2 during curing of standard concrete (ready mix or pre-cast) and (2) the use of steel slag as an alternative binder to cement that is the cured with CO_2 (pre-cast only)
Aggregates	Forming mineral carbonates	The route considered is the accelerated carbonation of waste residues, such as fly ash, to produce aggregates with properties similar to that of lightweight or manufactured aggregate.
Methanol	Hydrogenation	The route considered is the direct hydrogenation of CO_2 to methanol.
Formic Acid	Hydrogenation / Electrochemical reduction	The routes considered are the direct hydrogenation of CO_2 to formic acid through catalytic hydrogenation and the electrochemical reduction of CO_2 to formic acid.
Dimethyl Carbonate (DMC)	Reacting CO_2 and epoxides / Reacting CO_2 and methanol	Two routes are considered: (1) Transesterification of CO_2 derived cyclic carbonates (2) Electrochemical reaction of CO_2 with methanol.
Polycarbonate	Reacting CO_2 and epoxides	The original Asahi Kasei process of reacting CO_2 with epoxides, to get ethylene carbonate followed by subsequent reactions to BPA-PC.
Polyols	Reacting CO_2 and epoxides (catalytic co-polymerisation)	The route considered involves the direct use of CO_2 in polyols via the catalytic co-polymerization of epoxides (EO or PO) and CO_2. The product is polyethercarbonate polyols.
Middle Distillate Hydrocarbons	Hydrogenation	CO_2 conversion (via rWGS) to CO followed by Fischer-Tropsch conversion to synthetic crude which then undergoes hydrocracking/refining to produce the final fuels.
Synthetic Methane	Hydrogenation	The CO_2 methanation process considered is a variation of the Sabatier reaction called the TREMP process by Haldor Topsoe.
Dimethyl Ether (DME)	Hydrogenation	The route considered is a single-step process in which CO_2 is converted to methanol (catalytic hydrogenation) and dehydrated to DME in the same reaction vessel.
Ethanol	Electrochemical reduction	Electrochemical reduction of CO_2 to CO, followed by reaction with H2.
Methanol	Hydrogenation	The route considered is the direct hydrogenation of CO_2 to methanol.

2.2 Comparative Assessment

The overall aim was to assess commodities under four primary criteria: mitigation potential, market uptake potential, technical scalability, and other impacts. These criteria were first defined as shown:

CO_2 mitigation potential: The ability of the CCU route to lead to emissions abatement in the future, if there are no technology or economic barriers.

Market uptake potential: The ability of the CCU route to have an established future market in a low-carbon world, if there are no technology barriers.

Technical scalability: The ability of the CCU route to deploy globally or at a large scale, if there is significant market demand.

Other impacts: The extent of additional impacts that would occur through deployment of the CCU route.

A broad set of sub-criteria were investigated for all commodities to ensure a holistic comparison. A set of sub-criteria were identified based on broader factors that influence success in each of these areas. These sub-criteria were then investigated in the same manner for all commodities to ensure a fair and holistic comparison. The influencing sub-criteria are shown in Figure 1 with further explanations below.

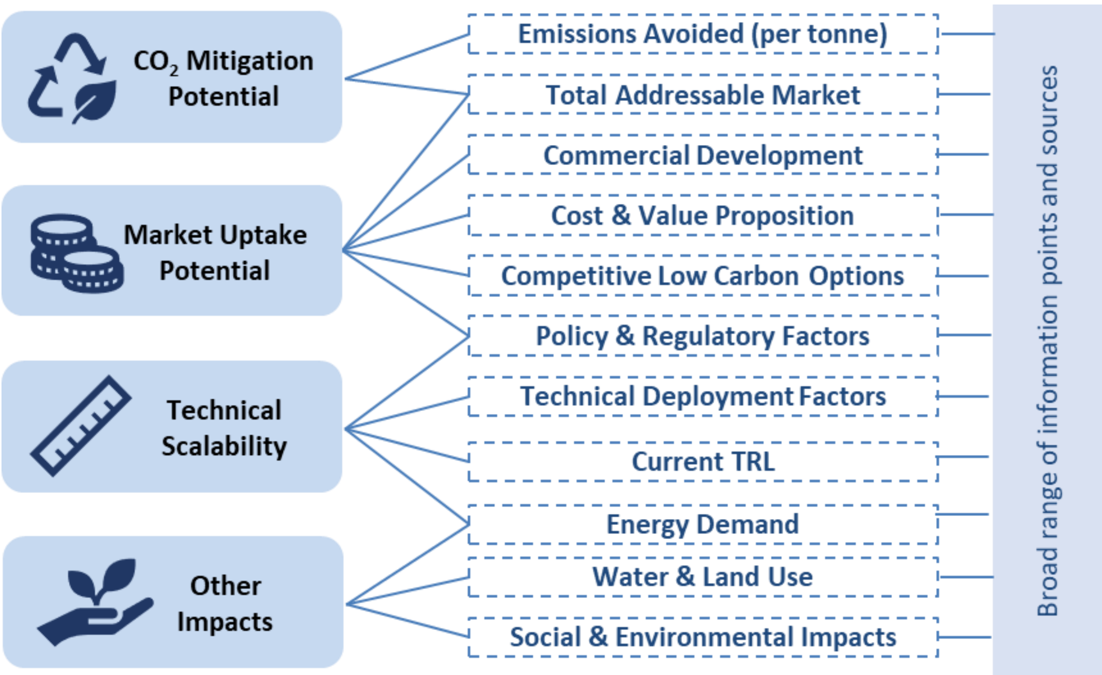


Figure 2: Approach for the assessment of CCU commodities: selection of sub-criteria influencing each of the primary criteria

Description of sub-criteria

1. **Emissions avoided (per tonne):** This sub-criterion considers the amount of CO_2 that is avoided through the CO_2 utilisation route when compared to the same commodity produced via the conventional pathway. This was evaluated through the interpretation of existing life cycle assessment (LCA) studies where available, alongside the authors judgement based upon technical details of the

conversion pathway. The aim was to assess commodities on mitigation potential rather than absolute emissions or CO_2 sequestration. Therefore, overall emissions avoidance was considered relative to the conventional pathway. Further detail on the use of LCAs and limitations of the assessment approach are included in Section **Error! Reference source not found.**. The sub-criterion influences a commodity's '*Mitigation Potential'*.

2. **Total addressable market:** Defined as the total market size (in units of mass) that the CCU commodity could theoretically address (technical potential), considering potential end-uses and current market sizes for conventional products. In most cases this is the size of the equivalent counterfactual market in 2019, however new applications and markets are also considered where there is obvious theoretical potential for expansion. The sub-criterion influences both a commodity's '*Mitigation Potential*' and '*Competitiveness and Market Potential*'.

3. **Commercial development[10]:** This sub-criterion considers various factors relevant to the successful commercialisation of new products or technologies, including the establishment of market interest, obtainment of investor backing, the development of licensing contracts or commercial sale of products, and type of developers involved (e.g. existing key players, established companies, start-ups, academic researchers). The sub-criterion influences a commodity's '*Competitiveness and Market Potential*'.

4. **Cost & value proposition[10]:** Defined as the extent to which the CCU route is cost competitive with the counterfactual or has the potential to bring added value, such as performance improvements or meeting sustainability requirements. The sub-criterion investigates the business case and drivers for the CCU route. The acceptability of cost premiums within the market is also considered. The sub-criterion influences a commodity's '*Competitiveness and Market Potential*'.

5. **Competitive low carbon options:** This sub-criterion considers whether there are alternatives that may compete with the CCU route from a low-carbon perspective, including whether these alternatives are already established and to what extent they might limit the market share available to CCU commodities. For example, synthetic fuels from electrolysis (e-fuels) would compete with biofuels, electric vehicles, and fuel-cell electric vehicles limiting the market share obtainable in a low-carbon world. The sub-criterion influences a commodity's '*Competitiveness and Market Potential*'.

6. **Policy & regulatory factors[10]:** Defined as the extent to which the CCU route could be successful without additional policy or regulatory support. This sub-criterion considers various factors relevant to how policy and regulatory factors may either be needed to support the uptake of a CCU route or how existing policies or regulations may act as a barrier to CCU uptake. The sub-criterion influences both a commodity's '*Competitiveness and Market Potential*' and '*Technical scalability*'.

7. **Technical deployment factors:** Defined as the ease at which the technology could be deployed at a large enough capacity to address the maximum possible market demand. This sub-criterion considers various factors including engineering challenges with deployment (e.g. equipment complexity), whether the technology can be installed as a retrofit or located onsite at an existing facility, and whether there are restrictions on deployment due to resource requirements or location limitations. The sub-criterion influences a commodity's '*Technical scalability*'.

8. **Current TRL:** Relates to the technology readiness level (TRL) of the CCU technology. The sub-criterion considers the stage of development that the technology has reached to date, ranging from

[10] Note that many CCU commodities perform less well on sub-criteria such as policy and regulatory or commercial development. This is partly due to the fact that the current energy and commodity system, including the policy, have evolved around the dominance of fossil fuels, so naturally CCU alternatives currently have lower market drivers, policy support and commercial interest.

lab-scale research, through demonstration in a relevant environment, to pilot and industrial scale operational demonstrations. The sub-criterion influences a commodity's '*Technical scalability*'.

9. **Energy demand:** This sub-criterion considers whether the CO_2 utilisation pathway has an increased or decreased energy demand relative to the conventional pathway[11]. The sub-criterion influences both a commodity's '*Technical scalability*' and '*Other Impacts*'.

10. **Water & land use:** This sub-criterion considers the impact that the CO_2 utilisation pathway has on water and land use compared to the conventional production route. For example, increased land-use due to large scale renewables deployment. The sub-criterion influences a commodity's '*Other Impacts*'.

11. **Social & Environmental:** This sub-criterion considers the various additional implications of adopting a CO_2 utilisation pathway. For example, reduced pollution from cleaner fuels, continued use of existing assets, lower use of hazardous chemicals, or avoidance of waste products. The sub-criterion influences a commodity's '*Other Impacts'*.

Several sub-criteria (emissions avoided, energy demand, water & land use, other impacts) were assessed through interpretation of existing life cycle assessment (LCA) studies where available. Further detail on the use of LCAs is included in Section **Error! Reference source not found.**.

Scoring system

A simplified scoring system for each sub-criterion was selected to allow a high-level comparison of all routes. Commodities were assessed on each sub-criterion and given scores to indicate whether they performed well (area of strength) or not so well (area of weakness). To ensure a transparent and comparable approach, the scoring system for each sub-criterion was described with two example scoring descriptions included below (Table 3, Table 4). The scoring descriptions for each of the sub-criterion are included in the Appendix.

Table 3: Description of the scoring system used to score the 'Cost & Value Proposition' sub-criterion for all commodities.

Scoring criterion scoring: Cost & Value Proposition

Score	Description
1	The technology is not cost-competitive. This is a major barrier for market demand.
2	The technology is not cost-competitive. This is a significant barrier for market demand.
3	The technology is unlikely to be cost-competitive with the counterfactual however drivers exist to place extra value on the route within the market (justifying payment of cost-premium)
4	There is a good business case for use of the technology resulting from cost savings or other added value (e.g improved performance)
5	There is a strong business case for use of the technology resulting from significant cost savings and/or additional value propositions

[11] The assessment is not based on absolute energy demand, although this information is included for context where available.

Table 4: Description of the scoring system used to score the 'Energy Demand' sub-criterion for all commodities.

Sub-criterion scoring: Energy Demand

Score	Description
1	The CCU process results in significantly higher energy consumption than the counterfactual route.
2	The CCU process results in slightly higher energy consumption than the counterfactual route.
3	The CCU process results in similar energy consumption to the counterfactual route.
4	The CCU process results in somewhat lower energy consumption than the counterfactual route.
5	The CCU process results in significantly lower energy consumption than the counterfactual route.

The scores follow a 1-5 scale with higher numbers used to show a more positive, beneficial, or stronger result. For the sub-criteria assessed via comparative LCAs, a score of three was given if the impact of the CO_2 utilisation route was comparable to the counterfactual, with higher / lower scores given for better / worse impacts respectively. For the other sub-criteria, the scoring method was chosen to highlight distinctions between the range of commodities investigated, with commodities that perform well relative to others scoring higher.

The sub-criteria scores are combined to give a high-level score for each of the primary assessment criteria. The approach used gives the primary criterion a score calculated from the **average of the sub-criteria** scores. Other options such as products and weighted averages were considered; however there is limited justification for the weightings, and for the purpose of the high-level comparison an average was deemed appropriate. In most cases, a good current performance in all sub-criteria is not essential for future success as actions can be taken to improve sub-criteria scores. Therefore, an average approach highlights the extent to which further support is needed, without unnecessary penalties for underperformance in a single area.

The scoring system is used as a simplified tool to highlight a commodity's strengths and weaknesses. It is not intended as a way to rank commodities. There are many variables impacting the success of CO_2 utilisation technologies and these are likely to vary both temporally and regionally. The scores are based upon the authors interpretations of publicly available data and in some cases high level estimations where data was not available. In many cases assumptions have had to be made either due to lack of data or because data is highly variable dependent upon specific factors, such as choice of electricity source or origin of counterfactual commodity.

2.3 Evaluation of avoided emissions

An appropriate and robust approach to evaluate and compare the avoided emissions of different CCU pathways would involve the use of comparative lifecycle assessment (LCA). Conducting commodity LCAs was not within the scope of this study and therefore evaluation of avoided emissions was expected to rely on LCAs available in the literature. Several challenges were identified with this approach, the details and implications of which are summarised below.

Life cycle assessment

Life cycle assessment is a useful tool for determining the environmental impact of a product. A lifecycle assessment aims to track material flows (energy, emissions, water etc.) associated with the lifecycle of a product, from the extraction of raw materials, their processing into a product, the use (and re-use/recycling) of the product and the end-of-life of the product, as well as transportation between steps and broader requirements. Lifecycle assessments are a useful tool for evaluating the environmental impacts of products and can be used to compare between routes ensuring all factors are considered. This study aimed to use lifecycle assessments to understand the mitigation potential, energy demands, land and water use of CCU routes. The benefits and challenges of using LCAs for this purpose are discussed below.

Lifecycle assessments are an appropriate way of evaluating environmental impacts of CCU routes. LCA is a useful methodology to quantify the environmental impacts of products, processes, services, companies and geographical regions. When applying the LCA methodology to study the environmental impacts of products, all life-cycle stages of the product should be considered. In this way, LCA can be used to compare technologies and scenarios. LCA has been recommended as an appropriate methodology to evaluate environmental impacts of CCU technologies. LCA studies are divided into four major phases: goal and scope definition, inventory analysis, impact assessment and interpretation.

The results of an LCA study can vary considerably with technical and methodical choices for the assessment. Lots of decisions are made when conducting an LCA assessment. These include selecting a representative functional unit and determining which processes to include within the system boundaries; the selection of the geographical location and the source of the different feedstocks/inputs to the CCU process (e.g. electricity source, hydrogen generation); the choice of allocation method if multi-functional processes are involved; the time horizon considered and the assumed lifetime of a product.

Appropriate boundaries of LCAs may differ depending on the product. The approach taken when conducting an LCA differs depending upon whether the product being assessed is identical or different to the conventional product it is being compared against. For instance, for products and fuels with an identical chemical structure and composition to their conventional counterpart, a cradle-to-gate approach is widely considered to be sufficient. This is because if the products are chemically identical, then their life-cycle phases and environmental impacts during use will be identical. Additionally, products which are used as a chemical feedstock will have multiple different potential uses, so it would not be possible to assess the carbon footprint arising during their use without assessing each different potential use separately. LCA system boundaries for products with different chemical structure and composition to their conventional counterparts however, should cover the entire life-cycle from cradle-to-grave. For instance, when comparing a synthetic fuel to a conventional fossil fuel, the synthetic fuel will perform differently and its environmental impacts during use will be different. In such cases, the LCA study needs to cover the entire life-cycle from cradle-to-grave. Published LCAs of different products therefore commonly use different system boundaries.

In order to improve the consistency, comparability and comprehension of LCAs several organizations have worked towards creating guidelines for practitioners conducting these assessments. For example, CO_2 *Sciences* and the *Global* CO_2 *Initiative* worked with numerous experts to develop the "Guidelines for CO_2 Utilization"[12].

Challenges and limitations

The novelty of many CCU technologies means that LCA studies may not yet exist. As many CCU technologies are rather new, there has been a lack of LCA studies on CCU options. Whilst the number of such studies is now growing, some of the commodities or production routes analyzed in this study do not yet have published LCAs making it difficult to elucidate the real life-cycle environmental impact of the route. For the purpose of this study, where suitable LCAs were not available a variety of other sources were used to draw an estimated life-cycle impact, often with simplifications or assumptions. Sources included academic papers

[12] Zimmermann et al. 2018, Techno-Economic Assessment & Life-Cycle Assessment Guidelines for CO_2 Utilization. [LINK]

looking at different environmental impact categories or processes involved in the CCU route, or in some cases higher-level publications or claims by manufacturers.

A number of inconsistencies and issues were found in the LCA studies of CCU technologies. Studies often use various methodological choices, which significantly influence the results obtained. Some of these choices include the definition of the functional unit (e.g. mass, energy content or technical performance), setting the system boundaries (e.g. excluding CO_2 capture), approaches to deal with multi-functional processes (i.e. substitution, system expansion or allocation), selection of the impact assessment method (and therefore inclusion/exclusion of some environmental impact categories) and considering the timing of capture and emission.

A common challenge when reviewing various LCA studies of the same product is incomplete reporting. It is common that some of the methodological choices mentioned above were not described in the studies, which significantly complicates comparability. This is aggravated by the number of other technical choices that considerably contribute to the final results, such as decisions about the feedstock supply (e.g. CO_2, hydrogen), energy sources (e.g. fossil or renewable) and geographical location. The source of feedstocks and energy are key factors when assessing the environmental performance of CCU products.

Implications for evaluation process

As outlined above, the LCAs of different products or different technologies are often not directly comparable and LCAs were not always available. It was therefore not possible within the scope of this study to produce comparable, quantitative estimates for the avoided emissions of the commodities assessed within a sufficient level of confidence. For this reason, the scores given for the ‘Emissions avoided (per tonne)’ sub-criterion are based on qualitative assessment criteria as outlined in Table 5. Scoring was based on the authors interpretations of the literature available and their understanding of technical factors relating to the conversion route. For this reason, scores may not directly correlate to the literature values of absolute or avoided emissions presented in the text, which have been included to highlight the existing data available.

Table 5: Description of the scoring system used to score the ‘Emissions Avoided (per tonne)’ sub-criterion for all commodities.

Emissions Avoided (per tonne)

Score	Description
1	The CCU process results in significantly more GHG emissions than the counterfactual route.
2	The CCU process results in slightly more GHG emissions than the counterfactual route.
3	The CCU process results in similar GHG emissions than the counterfactual route.
4	The CCU process results in somewhat less GHG emissions than the counterfactual route.
5	The CCU process results in significantly less GHG emissions than the counterfactual route.

3 Building Materials

This chapter investigates CCU developments in the building materials sector with a focus on concrete and aggregates. The global markets for these products are large with continued growth expected. Concrete is characterised as a low-value, high volume product which is used for a wide range of applications in the construction industry, with prominent end-uses in buildings and infrastructure projects. Its extensive global use results from the combination of impressive properties, such as its compressive strength, at low costs. The global concrete market has a value of over USD 700 billion with an estimated production exceeding 30 Gt product in 2019. Aggregates, such as crushed rock, sand, and gravel, are one of the key components of concrete, paired with cement and water, however they are also employed elsewhere for construction applications. They are used to provide bulk volume, stability, and strength. The aggregates market is predicted to grow to 50 Gt by 2030 and is split into different classes of product as shown in Figure 3. Continued growth is expected for both markets, with the greatest expansions in developing countries due to increasing housing and infrastructure projects.

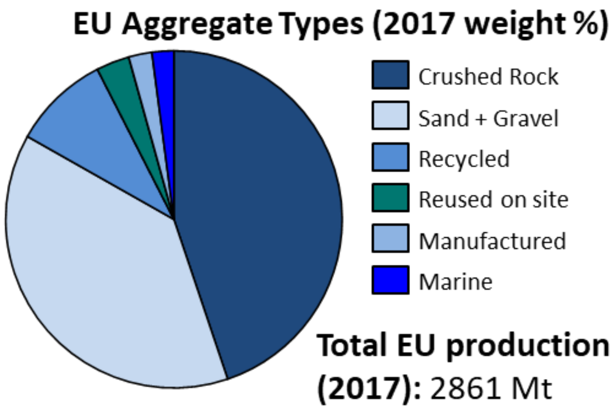


Figure 3: Breakdown of EU aggregate types by weight in 2017. Total EU production: 2861 Mt. Produced using data from UEPG (European Aggregates Association) available here: https://uepg.eu/pages/figures

The region with the greatest demand for construction materials is Asia, with China producing the largest amounts of cement globally. The localised production of concrete makes demand difficult to monitor however as concrete is approximately 10-15% cement, cement production is indicative of concrete demand. A global breakdown of cement production in 2019 is shown in Figure 4, with a total of 4.1 Gt of cement produced that year[13]. It is seen that China dominates, with over half of global demand, followed by India and Vietnam. After Asia, North America is the region with the next largest demand. Similar regional breakdowns are expected for aggregates.

- **Cement in the United States:** Approximately 90 Mt of cement was produced in the United States in 2019, a growth of 2.5% on 2018, with 70-75% of sales going to ready-mixed concrete producers. In addition, the United States imported 15% of its cement consumption, mostly from Canada, Greece, China, and Turkey.

[13] USGS 2020, Mineral Commodity Summaries [LINK]

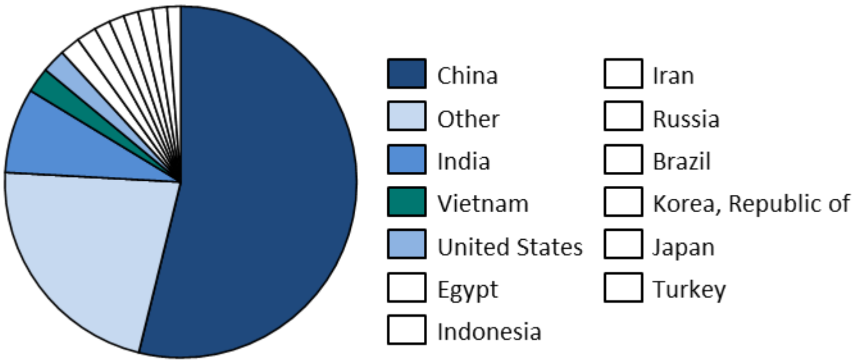


Figure 4: **Cement Production (2019 weight %).** Global breakdown of cement production (indicative of concrete production). Produced using data in USGS 2020, Mineral Commodity Summaries (page 43) [LINK]

Influential market characteristics:

- **Localised markets:** The nature of ready-mix concrete means that it is produced locally to where it is used, with production at many small, distributed sites. The bulk and weight of pre-cast concrete materials and aggregates also makes the use of local products favorable where these are available.
- **Low value, high volume:** Concrete and aggregate are low value products sold at high volumes. The low profit margins indicate that any increases in production costs are likely to be highly unfavourable for the market.
- **Limited alternatives:** The demand for both types of products is expected to grow and there are limited alternatives for substitution. Alternative options for decarbonisation of concrete include the lowering of cement emissions by process changes or by adoption of CCS at cement plants. Aggregates have comparatively low levels of emission intensity.
- **Conservative:** The construction industry is conservative in nature with building materials being highly standardised. In the past the sector has showed slow uptake of new products, making it difficult for novel materials to enter the market[43].
- **Competitive & Fragmented:** The global market consists of a large number of players and includes many smaller, localised companies. However, in some regions there has been a trend towards more vertical integration with international cement firms acquiring aggregate and concrete manufacturers.

Policy support for low-carbon building materials is limited. Some supply side policies exist with schemes such as the EU ETS placing limits on industrial emissions, including cement manufacturers. Demand side regulations are however typically not in place, meaning that consumers lack incentives to adopt lower emission or sustainable products. For example, building regulations often do not incorporate limits on the embedded emissions of the construction materials used. There are exceptions to this, with several countries developing public procurement rules or guidelines to favour low carbon products in public infrastructure projects. For example:

- In the UK, government buying standards require that new-build construction projects should achieve an ‘excellent’ rating when assessed via BRE’s Environmental Assessment Method (BREEAM)[14].
- In the Netherlands, a CO_2 Performance Ladder certification scheme was developed. This allows tenderers with the highest certification level to be given a 5% tender reduction[15].
- In Australia, two major public infrastructure clients in New South Wales use prescriptive requirements to drive sustainability. The Infrastructure Sustainability Council of Australia (ISCA) has also established the IS rating scheme.[15]

[14] DEFRA 2012, Government Buying Standards (GBS) for new build construction and major refurbishment [LINK]
[15] Kadefors et al, Designing and implementing procurement requirements for carbon reduction in infrastructure construction – international overview and experiences [LINK]

- In Sweden, the transport administration introduced increasing carbon reduction targets that, if exceeded, allow contractors to be awarded a bonus of approximately 1% of the contract sum[15].

3.1 CO_2 Utilisation Opportunities (Building Materials)

Applications of CO_2 utilisation in the building materials sector have focused on energetically favourable carbonation reactions in which CO_2 reacts with minerals to form a mineral carbonate. These reactions occur naturally but at low rates, so accelerated carbonation technologies have been developed for CCU purposes. The process involves exposing materials containing cations, such as calcium (Ca^{2+}) or magnesium (Mg^{2+}) ions, to higher than atmospheric concentrations of CO_2. It is energetically favourable for the CO_2 to react with such ions to form mineral carbonates ($CaCO_3$, $MgCO_3$) which then exist as ionic crystals in the material, permanently sequestering the CO_2 and adding mass to the material.

Variants of accelerated carbonation technologies have been applied to the two main mineral-containing construction materials: concrete and aggregates. The mineral carbonates produced from accelerated carbonation are the same compounds as those found naturally in rocks, such as limestone, and therefore the most obvious applications are in producing rock-based materials, such as concrete and aggregates. These materials are defined by their properties and components rather than exact compositions. Concrete is a composite material composed of fine and coarse aggregates that are held together by a binder, such as cement. Aggregate is used to refer to particulate or granular material such as sand, gravel, crushed stone, or manufactured particulates. The same types of reactions occur for both CCU routes, the differences are in how the technology is applied and the form and end-uses of the final product.

Developments have been driven by the enhancements that accelerated carbonation can have on material properties. Carbonation can be used to stabilise alkaline waste residues preventing leachates from entering the environment and making their reuse or disposal easier[16]. The formation of carbonate minerals during the curing of concrete can increase the strength of concrete, with added benefit of reduced curing time. Also, most simply, the incorporation of CO_2 into products provides additional mass which adds value to the product. Some of the specific accelerated carbonation applications under development, their technologies for applying the process, and their individual motivations are discussed and assessed in the following sections.

There are other CO_2 utilisation opportunities that are relevant to the building materials sector. These include the polycarbonate and polyurethane foams that are discussed later – Chapter 5– but also more novel developments in the use of CO_2 as a feedstock to produce specialised carbon materials, such as carbon black[17], carbon fibres[18,19], and carbon nanotubes[20]. These are described in Box 1.

[16] Gomes et al. Alkaline residues and the environment: a review of impacts, management practices and opportunities [LINK]
[17] KIT 2020. Press Release: From Greenhouse Gas to a High-tech Resource [LINK]
[18] Arnold et al. Energy-Efficient Carbon Fiber Production with Concentrated Solar Power [LINK]
[19] Ren et al. 2015, One-Pot Synthesis of Carbon Nanofibers from CO_2 [LINK]
[20] Ren et Licht, 2016. Tracking airborne CO_2 mitigation and low cost transformation into valuable carbon nanotubes. [LINK]

Box 1: CO_2 as a Feedstock for Specialist Carbon Materials

There have been novel developments in the use of CO_2 as a feedstock to produce specialised carbon materials, such as carbon black[17], carbon fibres[18,19], and carbon nanotubes[20]. Due to their superior properties, **carbon nanofibers and nanotubes** have potential to be principal components in high strength, light weight building materials, replacing emission-intensive steel and concrete in structural applications such as bridges and wind turbines[20]. Current production routes are however expensive and complex, with existing applications limited mostly to automotive and aerospace industries[18,19]. Furthermore, conventional routes are energy-intensive (requiring high temperatures and pressures), causing significant CO_2 emissions[18]. It is reported that the use of CO_2 as a feedstock for the production of these high-value carbon materials could lower energy consumption and be more economically viable[18,20]. Switching to CO_2-derived products therefore has the potential to lead to significant avoided emissions as well as to permanently sequester CO_2. One production pathway under development involves synthesis via electrolytic conversion of atmospheric CO_2 dissolved in molten carbonates using inexpensive steel or nickel electrodes[19]. C2CNT is a start-up that is developing the process.

This chapter assesses two CO_2 utilisation routes that use accelerated carbonation technology: CO_2 cured concrete and waste to aggregates.

3.1.1 CO_2 Cured Concrete

Concrete is a composite material composed of fine and coarse aggregates that are held together by a binder, typically cement and water. The production involves straight-forward mixing of components in correct proportions. When combined with water, conventional Portland cement undergoes a series of hydration reactions which cause it to set and harden, binding the aggregates together into a solid composite. These reactions occur at a relatively slow pace with full maturity of the concrete and the desired properties reached up to 28 days later[21]. The process of setting and continued hardening is known as curing. The market is split between concrete that is set at the point of use (ready-mix / cast-in-place), and concrete that is prefabricated into blocks or parts, such as tiles, sleepers, or pipes (pre-cast). The ready-mix market dominates.

The accelerated carbonation process can be applied during the curing stage of concrete manufacture. Liquid CO_2 can be injected whilst the concrete is being batched and mixed using a retrofit CO_2 injection system installed on the central mixer (prior to discharge into the truck)[22]. This simple retrofit approach can be applied to both ready-mix and pre-cast products and works with normal Portland cement. It has been commercialised by CarbonCure, with over 200 installations worldwide[23]. An alternative approach specifically for pre-cast products is to cure the products in an atmosphere with elevated CO_2 concentrations, such as by injecting CO_2 into sealed curing chambers. These routes typically use alternative binders, but other aspects of the manufacturing process are kept the same (mixing, molding) meaning the process can be adopted at existing pre-cast concrete manufacturing sites.

Several companies are commercialising technologies that apply accelerated carbonation during the curing of concrete, including:

- **CarbonCure (Canada):** Injects CO_2 whilst mixing concrete using a small modular device that can be retrofitted on existing equipment. Applicable to both ready-mix and pre-cast concrete. Used with conventional Portland cement, with limited CO_2 uptake. Deployed at over 200 sites.
- **Solidia Technologies (US):** Uses an alternative calcium silicate-based cement that cures with CO_2 rather than H2O. Applicable to pre-cast concrete due to use of a curing chamber.

[21] CoMS 2017 (DeCristofaro et al.), Environmental Impact of Carbonated Calcium Silicate Cement-Based Concrete [LINK]
[22] CarbonCure (Monkman) 2017, Calculating Sustainability Impacts of CarbonCure Ready Mix [LINK]
[23] Analysis of producers listed at: https://www.carboncure.com/producers/ [accessed Dec 2020]

- **Carbicrete (Canada):** Use of steel-slag as an alternative binder to cement, cured using CO_2. Applicable to pre-cast concrete due to use of a curing chamber.
- **VITO with ORBIX (Belgium):** 'Carbstone' product. Use of steel-slag as an alternative binder to cement, cured using CO_2. Applicable to pre-cast concrete due to use of a curing chamber.

The use of CO_2 during the curing of concrete may provide added benefits such as improved strength or reduced curing time. CarbonCure reported that using CO_2 during curing could improve the compressive strength of concrete, and therefore could offset strength reductions caused by lowering cement proportions, allowing a 5-8% reduction in cement use for the same strength[22]. This reduction in cement both reduces the carbon footprint of the concrete (as cement is emission-intensive to produce) and allows for cost-savings. Solidia Technologies reported that their process, using an alternative binder, could reduce curing times to within 24 hours and lower water consumtion[21]. This results from curing occurring via carbonation reactions rather than hydration reactions. The alternative binder used (calcium silicate-based cement) also has lower associated emissions than Portland cement[21].

Emission reductions are primarily due to the avoidance of cement, however permanent sequestration of captured CO_2 also occurs. The largest contributor to concrete CO_2 emissions is typically the cement, where considerable emissions result from the energy requirements and process of limestone calcination. The CO_2 utilisation pathways mentioned above either allow for reduced cement consumption, use an alternative lower-emission cement, or replace cement with a waste product such as steel slag. The avoidance of cement tends to be the dominant factor for emission reductions. This is particularly true for approaches using normal cement: for example, the curing of conventional concrete with CO_2 sequesters 0.1 kg CO_2 per tonne of concrete and allows for a 5% reduction in cement use that corresponds to an avoidance of 6.5 kg CO_2 per tonne of concrete[24]. The use of alternative 'CO_2 activated' binders with CO_2 curing chambers allows for greater sequestration of CO_2 compared to Portland cement. It is reported that using calcium-silicate based cement can allow concrete to contain in excess of 3%[25] by weight sequestered CO_2, with experimental results showing 220-240 kg of CO_2 sequestered per tonne of cement used[21]. Carbicrete claim a saving of 3 kg of CO_2 per concrete masonry unit (an approximately 18 kg cinder block[26]): 2 kg from the avoidance of cement and 1 kg from sequestration[27].

Additional positive impacts may arise from reduced cement use and the re-use of waste material. Production of cement requires approximately 9.6 GJ of energy per tonne, making it the largest contributor to the embodied energy of concrete[28]. This compares to 1.3 GJ per tonne for slag materials[28]. Similarly, cement use is the main differential for specific water consumption with 2.2 litres of water used per kilogram of cement[29]. Therefore, a reduction in cementitious material or replacement of cement with steel slag are expected to lower overall energy demands and lower water consumption. There are additional benefits if waste materials, such as steel slag, are used as a replacement for cement: firstly, a reduction in raw material extraction (via quarrying, for example) and secondly a reduction in the amount of waste sent to landfill.

Specific route assessed: Addition of CO_2 to conventional concrete mixtures during the mixing stage, allowing a reduction in the quantity of cement used for the same compressive strength.

[24] Based on data reported in: CarbonCure (Monkman) 2017, Calculating Sustainability Impacts of CarbonCure Ready Mix [LINK]
[25] Quoted in CoMS 2017 [see Footnote 21] but can also be calculated from the assumptions that up to 300 kg CO_2 is sequestered per tonne of cement[21], and that concrete is approximately 10% cement by weight.
[26] Qian Zhu (IEACCC) 2019. Developments on CO_2-utilization technologies. [LINK]
[27] Carbicrete Datasheet [LINK] [accessed Dec 2020]
[28] Wijayasundara et al. 2017, Comparative assessment of embodied energy of recycled aggregate concrete [LINK].
[29] Gerbens-Leenes et al. 2018, The blue and grey water footprint of construction materials: Steel, cement and glass [LINK]

Assessment: CO_2 Cured Concrete

Sub-criteria score

Mitigation Potential (Score: 5)

Emissions Avoided[a]: 5

The injection of CO_2 during curing of conventional concrete results in 4-6% lower emissions, corresponding to an abatement of 7-10 kg per tonne of concrete. This predominantly results from a reduction in cement consumption rather than CO_2 sequestration.

4-6% reduction

Cradle-to-gate GWP reduction cf. counterfactual.

Total Addressable Market[b]: 5

The global concrete market is currently estimated at 30 Gt with further growth projected. The market is split between ready-mix and pre-cast concrete. The CO_2 curing route assessed is able to address both segments.

30 Gt / yr

Todays global concrete market

Market Uptake Potential (Score: 5)

Commercial Development[c]: 5

The assessed route has been commercialized by CarbonCure, a company now in the growth phase. The technology is used in commercial operations by several cement manufacturers with installations at over 200 sites globally. The development of other similar CCU routes indicates market interest.

Policy & Regulatory Factors: 4

No significant barriers but limited support. The route could scale without support, but policy could enable increased demand by placing requirements on CO_2 footprint for new buildings and construction materials.

Total Addressable Market 5

Low Carbon Competition: 5

None known. CCS at a cement plant is an option but this doesn't displace the CO_2 curing route.

Cost & Value Proposition: 5

Cost reductions result from the lower cement requirements. Additional value from improved efficiency with quicker curing times and potential for an enhanced product performance.

Scalability (Score: 5)

Policy & Regulatory Factors 4

Technical Deployment Factors: 5

Systems are modular and the technology is straight-forward. The CarbonCure technology is installed as a retrofit at existing facilities with minimal disruption. It is possible that the dispersed nature of concrete production could present challenges for CO_2 distribution.

Current TRL: 5

Technology has been adopted at several sites.

TRL 9 | Multiple At-Scale Operations

Energy Demand: 5

Low energy requirements for the process as carbonation is exothermic. Reduction in lifecycle energy consumption dominated by reduction in cement consumption.

Low Energy Demand

Other Impacts (Score: 4)

Water & Land Use: 4

Water use is similar for most production steps (concrete mixing, aggregate preparation) however overall water use is lower due to reduced cement use. Land use is similar, with reductions in cement use balanced by potential for increased use of aggregates.

Reduced Water Consumption

Energy Demand 5

Social & Environmental Impacts: 5

Potential biodiversity improvements due to reduced mining and reduced waste associated with some routes.

(a) CarbonCure (Monkman) 2017, Calculating Sustainability Impacts of CarbonCure Ready Mix
(b) ICEF 2017, Carbon Dioxide Utilisation (CO2U). ICEF Roadmap 2.0.
(c) Analysis of producers listed at: https://www.carboncure.com/producers/ [accessed Dec 2020]

Assessment Outcomes

- **CO_2 Mitigation Potential:** The injection of CO_2 during curing of conventional concrete results in 4-6% lower cradle-to-gate emissions[22] corresponding to an abatement of 7-10 kg per tonne of concrete[30]. This predominantly results from a reduction in cement consumption rather than CO_2 sequestration. This route could be applied to both ready-mix and pre-cast concrete markets, with a total addressable market of 30 Gt per year[31]. Therefore, the use of CO_2 as a feedstock within concrete production could lead to abatement levels on the order of 300 Mt of CO_2 per year. Other CCU technologies applicable to just pre-cast products allow for increased sequestration of CO_2 using alternative cements, with these cements also having lower production emissions.
- **Market Uptake Potential:** CO_2 curing technologies have the potential to achieve high levels of market uptake due to their cost-competitiveness and additional value propositions. If the cost of CO_2 purchased can be balanced by cost-savings due to lower cement consumption, then CCU concrete can be cost-competitive with the conventional product. Some technologies have already been commercialized, with CarbonCure installations at over 200 cement sites globally[23]. Policy mechanisms could enable further uptake, for example by placing requirements on CO_2 footprint for new buildings.
- **Technical scalability:** The technology is expected to scale easily, with systems being modular and using straight-forward principles that should not present engineering difficulties. The CarbonCure technology is installed as a retrofit at existing facilities with minimal disruption. One consideration is the high dispersion and number of cement sites, requiring technology to be installed at multiple locations. This could make CO_2 distribution to the sites more challenging than other CCU options. Energy demand is not expected to be a barrier as the route has low energy requirements.
- **Other Impacts:** Additional impacts, such as improvements in biodiversity, may arise from a reduction in mining (associated with lower cement use) and reduced waste for the carbonation of alkaline waste routes. The lower cement use may also decrease overall life-cycle water consumption.

3.1.2 Aggregates from waste

Alkaline residues are produced as waste products by several industries and their disposal can be costly. Each year around 2 billion tonnes of alkaline residues are produced globally by industries such as steel production, alumina extraction, cement production, and coal-fired power generation[32]. These waste residues can release alkaline leachates (Ca^{2+}, Mg^{2+}, Na^{+}) over time and can be an environmental hazard if not disposed of correctly (for example, if allowed to generate dust or be infiltrated by water)[32]. Impacts associated with alkaline leachates from waste residues include biological impacts and increased mobility of other contaminants[32]. The commonly adopted disposal solution is waste treatment (solidification/stabilization) followed by storage in waste-piles or landfill[32]. Regulations on waste treatment and the costs of waste treatment ('gate fees') vary by country but can be considerable. For example, in Australia, immobilisation costs for solid waste can be up to \$300 per tonne, with other treatments (consolidation/neutralisation) up to \$900 per tonne[33]. Storage costs for wastes including high toxicity contaminants can be considerably more.

The accelerated carbonation process can be used to stabilise alkaline waste residues allowing their re-use as aggregate materials. CO_2 **is permanently sequestered.** The accelerated carbonation process can be used as a treatment to stabilise waste residues, with CO_2 reacting with potential leachates (Ca^{2+}, Mg^{2+}) to form stable mineral carbonates[32]. It has been estimated that in theory a total of 700-1200 Mt of CO_2 could be sequestered globally each year for treatment of wastes such as steel slag and cement kiln dust, with other sources suggesting 1 Mt and 7 Mt per year for wastes in the UK and USA respectively[32]. The treated wastes

[30] Using a benchmark value of 393 kg CO_2e per m3[22] and a density of 2400 kg per m3 gives a benchmark of 163 kg CO_2e per tonne concrete for conventional production.
[31] ICEF 2017, Carbon Dioxide Utilisation (CO_2U). ICEF Roadmap 2.0. [LINK]
[32] Gnomes et al. 2015, Alkaline residues and the environment: a review of impacts, management practices and opportunities [LINK]
[33] Marsden Jacob Associates 2014, Estimate of the cost of hazardous waste in Australia [LINK]

are re-evaluated after treatment and, providing 'end-of-waste' recognition is received, can then either be safely disposed of or re-used as a type of manufactured aggregate.

Treatment of wastes is the main business case, however there is also a large market for manufactured aggregates. The avoidance of expensive gate-fees for waste disposal is thought to be the dominant business driver for waste-producers adopting accelerated carbonation technology. This is sometimes combined with valuable metal extraction processes to generate additional revenue. The resultant aggregate is also a valuable product with comparable end-uses to the 'manufactured/lightweight' class of aggregate. This class of aggregate has a market of around 1 Gt per year – a small fraction (approximately 2%) of the total aggregate market, which is mostly dominated by higher-quality natural aggregate[34].

CO_2 utilisation technologies are used commercially and could be installed as a containerised system using CO_2 directly from flue gas. Carbon8 Systems developed an accelerated carbonation technology that has been used in commercial facilities since 2012, with three plants now being operated in the UK by OCO Technology to treat air pollution control residues[35,36]. Carbon8 Systems has since developed a containerised system 'CO_2ntainer' that can be installed onsite at a waste-producing facility and use CO_2 from flue gas directly[37], taking advantage of the typical co-location of waste residues and CO_2 sources. In 2020 Carbon8 Systems obtained a contract for delivery of such a system to a global cement manufacturer[38]. Several other companies are on the path to commercialising carbonation technologies for the treatment of alkaline wastes, including Carbicrete and Vito with ORBIX.

It is claimed that more CO_2 is sequestered in the products than emitted in their manufacture, making them carbon negative. Emission benefits for this CCU route are dominated by the permanent sequestration of CO_2 in the product. Conventional aggregates are not emission-intensive (approximately 4.3 kg CO_2 emitted per tonne for primary aggregates[39]) so any additional benefits from the avoidance of these products is likely to be minimal. It is claimed that more CO_2 is sequestered than is emitted during aggregate manufacture, with a cradle-to-gate CO_2 footprint of -44kg CO_2 per tonne of aggregate reported[40]. Additional benefits include the potential for a reduction in mining of fresh aggregate material and reduction of wastes.

[34] Assuming a global aggregate market of 30-50 Gt[31] with the same percentage of manufactured/lightweight aggregates as produced in the EU in 2017, given by 'UEPG Provisional Estimates of Aggregates Production - 2018 Data' [LINK]
[35] OCO Technology, previously Carbon8 Aggregates, timeline available here: https://oco.co.uk/about-us/
[36] Carbon8 Aggregates was an offshoot company of Carbon8 Systems – see REF impact case study "Treating waste with carbon dioxide: growth of spinout Carbon8 Systems" here: https://impact.ref.ac.uk/casestudies/CaseStudy.aspx?Id=29983
[37] https://c8s.co.uk/a-scalable-approach/ [accessed Dec 2020]
[38] Carbon8 Systems 2020, Press Release: Carbon8 Systems to deploy its pioneering technology at Vicat Group cement company in France [LINK]
[39] Mineral Products Association 2019, Sustainable Development Report 2009 [LINK]
[40] OCO Technology FAQs [LINK]

Assessment: Aggregate from Waste

Sub-criteria score

Mitigation Potential (Score: 5)

Emissions Avoided[(a)]: 5

The route offers permanent sequestration of CO_2, with claims that more CO_2 is sequestered than is emitted over the aggregate's lifetime. One product claims an absolute GWP of -44 $kgCO_2e$/t aggregate.

> 100%

Reduction in GWP cf. counterfactual per tonne aggregate

Total Addressable Market[(b)]: 4

The accessible markets for CCU aggregates are that of the lightweight or manufactured classes of aggregate. The existing market for this type of aggregate totals approximately 1 Gt with demand exceeding supply in some regions.

1 Gt / yr

Todays manufactured aggregate market

Market Uptake Potential (Score: 4)

Commercial Development: 4

CCU technologies have been used in commercial facilities since 2012. Demand exists from industries that wish to avoid waste disposal fees. Carbon8 Systems obtained a contract for delivery of its technology to a global cement manufacturer. Several other companies are commercializing their technologies including Carbicrete and ORBIX.

Policy & Regulatory Factors: 3

Dependency on high waste disposal fees and end-of-waste regulations. Policy could increase demand by placing requirements on CO_2 footprint for new buildings. Product specifications can act as a barrier for sale of the aggregates.

Total Addressable Market 4

Low Carbon Competition: 5

The CCU route is distinct in its business model for processing waste.

Cost & Value Proposition: 5

Value gained from avoidance of waste-disposal fees and potential to extract valuable metals from waste. The resultant aggregate can be sold at a competitive market price as it is not the main revenue driver.

Scalability (Score: 4)

Policy & Regulatory Factors 3

Technical Deployment Factors: 4

The technology is straight-forward and modular, with the potential to install a containerized system at an existing site. Waste residues are required as a feedstock, which may restrict deployment locations and scale.

Current TRL: 5

Deployment of 3 at-scale operations in the UK, one operational since 2012.

TRL 9 | Multiple At-Scale Operations

Energy Demand: 3

Energy consumption will depend upon the pre-treatment and transportation of wastes. The carbonation reaction is exothermic and overall energy demand may be similar to the existing route (low).

Low

Other Impacts (Score: 4)

Social & Environmental Impacts: 5

Benefits include the re-use of waste material, the potential for simultaneous recovery of minerals, and a reduction in mining of primary aggregate.

Energy Demand 3

Water & Land Use: 5

Reduction in land use – waste disposal, mining. Water use expected to be lower.

(a) OCO Technology FAQs

(b) Assuming a global aggregate market of 30-50 Gt (ICEF 2017) with the same percentage (2%) of manufactured/lightweight aggregates as produced in the EU in 2017, given by 'UEPG Provisional Estimates of Aggregates Production - 2018 Data'

Assessment Outcomes

- **CO_2 Mitigation Potential:** The CCU route offers permanent sequestration of CO_2, with claims that more CO_2 is sequestered than is emitted over the aggregate's lifetime making in carbon negative. An absolute GWP value of -44kg CO_2 per tonne[40] of aggregate has been claimed. Typical emissions for non-CCU primary aggregate are around 4.3 kg CO_2e/tonne. The route can address the manufactured aggregates market which currently has a size of approximately 1 Gt per year. Addressing this entire market would give a mitigation potential of the order of 50 Mt CO_2-eq per year. It is possible that market size could however increase with greater supply of these aggregates, and the route is not necessarily scaled by aggregate demand but rather by waste residue supply which has a greater market.
- **Market Uptake Potential:** Accelerated carbonation technologies have been used in commercial facilities since 2012, with multiple companies commercially developing their technologies. An example is Carbon8 Systems who have obtained a contract for delivery of its technology to a leading global cement manufacturer. Demand for the CCU routes exists from industries that wish to avoid high waste disposal fees, with the route having a business case for converting waste residues (such as fly ash) to a product with end-of-waste status. Market uptake of the route is therefore dependent upon regional policies and regulatory factors, requiring high disposal fees to exist and for the aggregate to be recognized in regulations as end-of-waste. As the resultant aggregate product is not the main revenue driver, it is expected that it could be sold at a competitive market price. Identified barriers to uptake are prescriptive product specifications and the conservative nature of the construction industry. Uptake is expected to be easier for less-critical applications.
- **Technical scalability:** Deployment of the technology is not expected to present engineering challenges as the technology is straight-forward and modular, with some routes offering the potential to install a containerized system at an existing site. Technical scalability could however be limited by the availability of waste residues, energy requirements for their pre-treatment, and transportation factors.
- **Oher Impacts:** Benefits include the re-use of waste material, the potential for simultaneous recovery of minerals, and a reduction in mining of primary aggregate. Both life-cycle land and water use are expected to be lower.

3.2 CCU Strengths, Weaknesses & Discussion (Building Materials)

The primary criteria results for the assessed routes, which involved accelerated carbonation technologies, are shown in Figure 5. The routes performed well in all categories, implying that the use of CO_2 as a feedstock for building materials has the potential to:

- **Achieve high levels of emission mitigation:** These routes result in significantly less GHG emissions per tonne, which combined with the large potential market size offers significant mitigation potential. The routes also offer permanent CO_2 sequestration.
- **Receive strong market demand:** These routes have large potential markets, good commercial development, and a strong business case based on cost competitiveness and additional value.
- **Effectively scale production:** The technologies are simple, technically well developed, and easy to scale. They can be installed on existing sites as a retrofit or containerised addition. The energy consumptions are similar to or less than existing routes.
- **Realise additional positive impacts:** The routes have additional beneficial impacts associated with reduced mining/quarrying and reduction in waste.

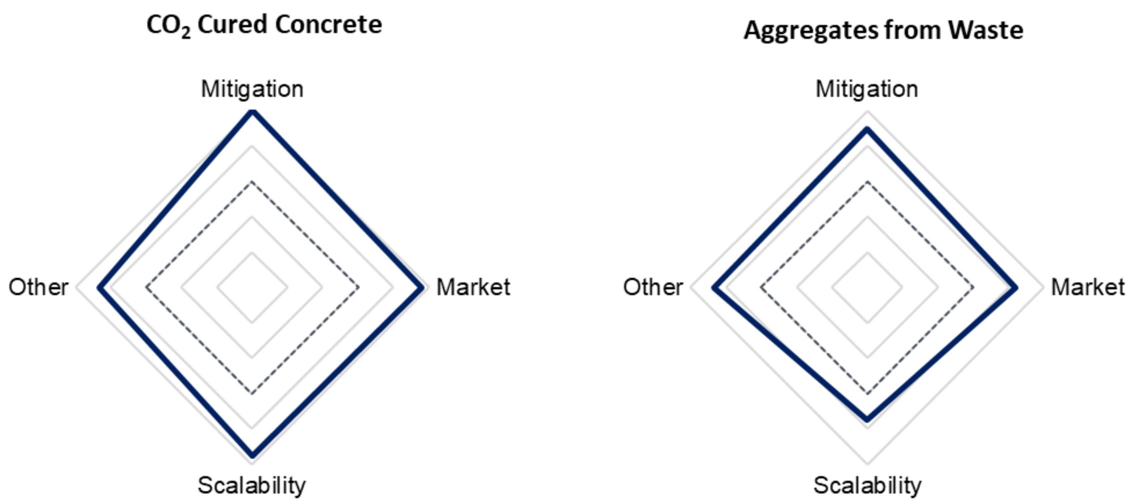


Figure 5: Radar plot of primary criteria scores (1-5) for **building materials,** with higher scores indicating an area of strength. The approach to scoring is detailed in Section 2.2 of this report and follows a comparative approach between all commodities investigated. **Mitigation:** The ability of the CCU route to lead to emissions abatement in the future, if there are no technology or economic barriers. **Market:** The ability of the CCU route to have an established future market in a low-carbon world, if there are no technology barriers. **Scalability:** The ability of the CCU route to deploy globally or at a large scale, if there is significant market demand. **Other:** The extent to which any additional impacts resulting from CCU deployment are beneficial (high score) or detrimental (low score).

Compared to CO_2-cured concrete, the waste-to-aggregates route has a lower addressable market size and lacks an advantage of lower energy demands. Although both routes have large addressable markets, the addressable concrete market is an order of magnitude larger than the addressable aggregates market. The CO_2-cured concrete route can be applied to the majority of existing concrete production whereas aggregates from waste target a smaller sub-set of the aggregate market. This difference led to concrete performing slightly better in the assessment for both mitigation potential and market uptake potential. For the concrete route, the assessment suggested that energy requirements could be lower than conventional production however this was not necessarily the case for the aggregates route. This led to the concrete route having a slightly better score for scalability.

The routes had some limitations related to policy and regulatory factors and technical deployment factors. There is a lack of dedicated policy or regulatory support for low carbon building materials and market uptake could be further enabled by the introduction of support mechanisms, such as regulations on the CO_2 footprint of new buildings. The value proposition for the waste-to-aggregates route is reliant on high waste-disposal fees, which exist in some regions but not others, as well as the product being designated as 'end-of-waste' by regulations in the region. This is a limitation that may restrict the regions in which there is market demand for the route, impacting uptake and/or scalability. Furthermore, the aggregates route requires a supply of waste residues and is typically located at the site where waste residues are produced. The concrete route assessed is installed at existing ready-mix facilities which are typically highly dispersed with a range of operators. These are minor limitations that could impact the ability of the routes to scale to reach the full potential market demand.

Regional Considerations

Waste-to-aggregates is likely to be most successful in regions which generate suitable waste residues, have high costs for waste disposal, and appropriate end-of-waste requirements. CO_2-cured concrete may be more favourable in areas with high cement costs or where CO_2 emitters are co-located with concrete producers. Existing CCU developers of building materials are located in North America and Europe.

RD&D, Evidence Gaps & Uncertainties

There were evidence gaps and uncertainties when assessing lifecycle environmental impacts. No full LCAs were found for the aggregate-to-waste route assessed.

4 Chemicals

Carbon containing primary petrochemicals are the key building blocks for many common chemicals and polymers. Chemicals derived from petroleum or natural gas, known as petrochemicals, account for 90% of the total feedstock demand for chemical production today[41]. Petrochemicals primarily consist of olefins (ethylene, propylene), aromatics (benzene, xylene, toluene) and methanol. These can be used as products themselves (such as methanol as a solvent) but are more commonly transformed into higher-value chemical and polymer products. Olefins for example are used to make polyethylene and polypropylene (polyolefins), the most commonly manufactured plastics in Europe, whilst methanol is used primarily to produce formaldehyde (itself a chemical intermediate) as well as octane boosting fuel additives. Petrochemicals account for 14% and 8% of the worlds total primary demand for oil and natural gas respectively[41] with demand increasing.

Asia accounts for over half of the petrochemicals market by value. The petrochemicals market was valued at USD 441 billion in 2019, of which approximately 55% was attributed to the Asia Pacific region[42]. Growth is expected, with increasing demand for methanol as a fuel additive and growth in polyolefins demand associated with end-uses in the packaging, automotive and construction sectors. The market is characterised by low margins and a high dependency on feedstock costs.

4.1 CO_2 Utilisation Opportunities (Chemicals)

The CO_2 utilisation routes being developed in the chemicals sector typically start by converting CO_2 to single carbon products, such as formic acid, carbon monoxide, methane, or methanol. Several CO_2 conversion pathways are being investigated for upgrading CO_2 to value-added chemicals, with two routes of interest being catalytic hydrogenation (reacting CO_2 and hydrogen) and electrochemical reduction (reducing CO_2 to CO, which can subsequently react with hydrogen). The requirement for hydrogen as a feedstock means that these routes are typically energy intensive, with low carbon production of hydrogen necessary to achieve emission benefits. The products derived from these routes are identical to fossil derived chemicals, meaning they can be incorporated into existing supply chains as direct substitutes.

The CO_2 acts as an alternative to fossil-based carbon sources. It is only temporarily sequestered. CO_2 utilisation allows the typically fossil-origin carbon atoms within common chemicals to instead be derived from captured CO_2, thus recycling the carbon atoms and avoiding the use of carbon from fossil resources. The CO_2 that is sequestered in the product is released at the chemicals end-of-life, such as when the chemical degrades, with retention times likely to be less than 10 years[43]. The mitigation potential of CO_2 derived chemicals therefore arises due to avoidance of fossil production routes, with CO_2 only mitigated if the CCU production route has lower levels of emissions in comparison.

A selection of chemicals that can be produced from CO_2 as a feedstock are discussed and assessed in the sections below. The chapter focuses on the chemical applications of these routes, with methanol as a fuel discussed later in section 6.1.5.

4.1.1 Methanol

Methanol can be used as a solvent, as a fuel, or as a chemical-intermediate in the production of higher-value chemicals. Figure 6 shows a breakdown of global methanol demand by end-use in 2019. Global market demand for methanol was around 98 Mt in 2019 with 20% of this being used for alternative fuels (DME, biodiesel) or gasoline blending[44]. As a primary, single carbon chemical (CH_3OH) methanol is used as a building block for producing higher value chemicals such as formaldehyde, acetic acid, DME, and MTBE. There is also an emerging market for methanol as a feedstock for production of olefins and gasoline, driven by the use of coal-derived methanol in countries such as China, where crude-oil is less easily available (see **Box 2**). This

[41] IEA 2018, The Future of Petrochemicals [LINK]
[42] https://www.grandviewresearch.com/industry-analysis/petrochemical-market
[43] IEA 2019, Putting CO_2 To Use
[44] Data is from the MMSA shared via the Methanol Institute, available here: https://www.methanol.org/methanol-price-supply-demand/

section focuses on the use of methanol as a chemical intermediate, with the use of methanol and its derivate DME as a fuel discussed in Chapter 6.

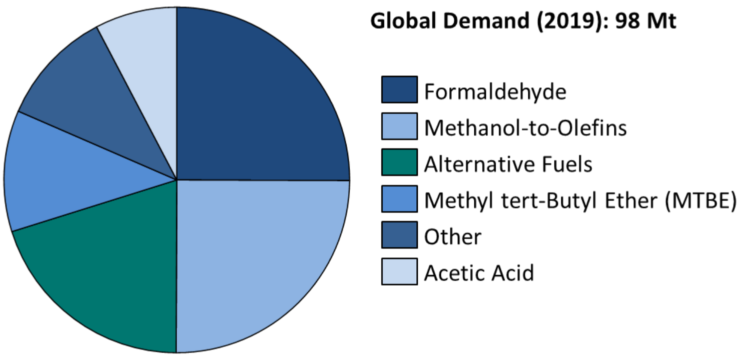


Figure 6: Global demand for methanol by end-use in 2019. Breakdown is by mass (volume) with the total demand being 98 Mt. Original data is from the MMSA via the Methanol Institute, available here: https://www.methanol.org/methanol-price-supply-demand/. Alternative fuels includes gasoline blending, DME and biodiesel.

Conventional methanol is typically derived from natural gas. Currently, methanol is produced by the hydrogenation of carbon monoxide, where pressurized syngas (carbon monoxide and hydrogen) reacts in the presence of a catalyst. Syngas is mostly produced by steam reforming of natural gas or by partial oxidation of solid carbonaceous materials. The cradle-to-gate emissions of methanol produced from fossil sources are estimated to be in the range of 0.68 - 1.08 t CO_2 eq/t methanol[45], with variations expected due to location and method. Syngas production is the main source of emissions.[46]

Methanol can be produced from feedstocks of CO_2 and hydrogen. Emissions are lower than conventional routes if renewable electricity is used. The catalytic hydrogenation of CO_2 and hydrogen to produce methanol is a well-studied CO_2 utilisation pathway. The route typically involves use of a Cu/ZnO/Al2O3 catalyst and low-carbon hydrogen from renewable water electrolysis, although other catalysts such as In2O3 and Ga2O3 metal oxides have been recommended[47]. As with other chemical routes, the requirement for low-carbon hydrogen makes this CCU pathway energy intensive. Several studies have concluded that methanol produced from CO_2 has a lower global warming impact than that produced from fossil sources if renewable electricity is used for water electrolysis[48,49,50]. One study reports cradle-to-gate emissions between -1.2 and -1.3 t CO_2-eq / t methanol in a best case CCU scenario[64]. Another study reports a cradle-to-gate avoidance of 1.53 t CO_2 / t methanol compared to methanol from natural gas, with the CCU methanol having a footprint of -0.67 t CO_2 compared to 0.85 t CO_2 per tonne of methanol[51]. Cradle-to-gate emissions for the conventional route are however variable with location and method (0.68-1.08 t CO_2-eq / t methanol)[64] meaning that the CO_2 mitigated is also variable.

Technologies have been proven in small-scale plants with CCU products marketed in Europe. The most established CO_2-to-methanol project is the George Olah Renewable Methanol plant in Iceland that was commissioned in 2011 by Carbon Recycling International (CRI)[52]. This plant has a capacity of 4 kt methanol per year with CO_2 sourced from the flue gas of a geothermal power plant and electricity from the Icelandic grid. Since 2012, their methanol has been sold commercially to clients in Europe and China under the brand name Vulcanol[52], although this is thought to be mostly for fuel applications. CRI plan to license their technology and have received their first commercial 'contract to deliver', which will see a commercial-scale plant built for a

[45] Artz et al. 2018, Sustainable Conversion of Carbon Dioxide: An Integrated Review of Catalysis and Life Cycle Assessment..
[46] Philibert, C. 2017, Renewable energy for industry. Paris: International Energy Agency.
[47] Ronda-Lloret *et al*. 2019, A Critical Look at Direct Catalytic Hydrogenation of Carbon Dioxide to Olefins [LINK]
[48] Artz et al. 2018, Sustainable Conversion of Carbon Dioxide: An Integrated Review of Catalysis and Life Cycle Assessment
[49] Pontzen et al. 2011, CO_2-based methanol and DME - Efficient technologies for industrial scale production
[50] Thonemann et al. 2020, Environmental impacts of CO_2-based chemical production: A systematic literature review and meta-analysis
[51] Bazzanella et Ausfelder 2017, Low carbon energy and feedstock for the European chemical industry. Technical study.
[52] Carbon Recycling International website [accessed Feb 2021] – George Olah Renewable Methanol [LINK] and Vulcanol [LINK]

company in China[53]. CRI are also developing a large scale project in Norway that would have capacity of 100 kt of methanol per year if approved[54].

The CO_2 utilisation route is more expensive than fossil production with costs dominated by electricity prices. The cost of methanol from CO_2 has previously been estimated to be at best-case twice the cost of fossil methanol[55,56]. Costs however are highly dependent upon the cost of the hydrogen and CO_2 feedstocks, with electricity costs for hydrogen production via water electrolysis being a dominant variable. The impact of hydrogen, CO_2 source and electricity choices on the cost of CCU methanol production is investigated further in our parallel study, Reality Check: CO_2 Hydrogenation.

The CO_2 utilisation route results in increases in energy, water, and land use. A recent study that considered CO_2 capture, hydrogen production, their conversion to methanol and associated infrastructure estimated a 45% increase in water depletion compared to the conventional route[57]. 70% of this water depletion was associated with hydrogen production[57]. Hydrogen production is also the dominant factor for energy consumption, with the electricity consumption per tonne of methanol totalling approximately 10 MWh[58] for CCU compared to 0.3 MWh for the conventional route[59]. There is also data to suggest that land use may increase considerably[60].

Box 2: Methanol-to-Olefins[61]

Methanol can be upgraded to both fuels and chemicals, allowing a broad range of possible end-uses. To date, pathways from fossil methanol to high value chemicals and fuels have proved attractive in regions with abundant coal or gas reserves but with little or no domestic oil production. In the long-term, if fossil feedstocks are to be avoided then CCU methanol provides a pathway to the production of polymers, such as polyethylene (polyolefins), and fuels, such as dimethyl ether (DME) and gasoline, via a pre-established methanol-to-DME/olefins/gasoline reaction pathway.

CCU methanol provides a low-carbon route to producing polyolefins such as polyethylene. The methanol-to-olefins (MTO) process was first introduced in 1981 by Union Carbide (now Honeywell UOP). Several commercial scale plants exist for the conversion of fossil-methanol to olefins, most prevalently in China for coal-to-olefins, with capacities up to 0.8 Mt per annum. This same technology could be used to upgrade CCU methanol to light olefins (ethylene, propylene), which can then be polymerised to common plastics such as (high-density) polyethylene. This is an alternative to the conventional fossil route of steam cracking crude-oil derivatives. It is estimated that currently 12% of fossil-methanol produced is used for the MTO process.[62]

In the long-term, 30-80% of olefins could be produced using CCU methanol. A 2017 report for CEFIC[63] investigated low carbon feedstocks for the European chemical industry, including modelling of deployment scenarios. In their notably ambitious intermediate scenario (steadily increasing deployment of breakthrough technologies), olefins produced via the CCU route of hydrogen-based methanol accounted for 30% of European olefin production in 2050, with remaining production from bio-based routes or continued fossil use. In their maximum scenario (100% deployment of new technologies), the CCU route to olefins accounted for 85% of olefin production, with the remaining 15% from bio-based routes. The total present-day global market for polyolefins is roughly 150 Mt.

53 CRI 2019, Press Release: Agreement Signed For CRI's First CO_2-To-Methanol Plant In China [LINK]
54 CRI 2020, Press Release: Commercial-scale ETL plant under development in Norway [LINK]
55 ECOFYS and Imperial College London 2017, Assessing The Potential Of CO_2 Utilisation In The UK (for BEIS). [LINK]
56 Perez-Fortes et al. 2015, Methanol synthesis using captured CO_2 as raw material: TEA and Environmental Assessment [LINK]
57 Meunier et al. 2020, Alternative production of methanol from industrial CO_2.
58 Internal estimate. Broadly aligned with DECHEMA 2017, Low carbon energy and feedstock for the European chemical industry [LINK]
59 Ecoinvent 3.7 dataset, 2020. Methanol production, from synthetic gas, RoW, Allocation, cut-off.
60 Thonemann 2020, Environmental impacts of CO2-based chemical production: A systematic literature review and meta-analysis
61 Text within the box is duplicated from the parallel study 'CO_2 Utilisation Reality Check: Hydrogenation Pathways'
62 Makarand R. Gogate 2019, Methanol-to-olefins process technology: current status and future prospects
63 DECHEMA 2017, Low carbon energy and feedstock for the European chemical industry

Assessment: Methanol as a Chemical Intermediate

Sub-criteria score

Mitigation Potential (Score: 3)

Emissions Avoided[a]: 4

CCU methanol has a lower global warming impact than fossil methanol if low-carbon electricity is used for water electrolysis. Mitigations of the order of 1.5 t CO_2 avoided per tonne of methanol are reported.

1.5 t CO_2 / t — **Cradle-to-Gate** emission reduction per tonne of methanol

Total Addressable Market[b,c]: 2

Methanol has an existing market of 80 Mt as a chemical intermediate, of which 25 Mt is used for olefins via MTO process. The global polyolefins market is in the region of 200 Mt olefin. This could in theory be accessed by methanol if the MTO process were to be used for all olefins production.

80 Mt / y — Existing market for methanol as a chemical

Market Uptake Potential (Score: 3)

Commercial Development: 4

Commercial interest is focused on CCU methanol as a sustainable fuel. CRI markets its CCU methanol commercially as a fuel in Europe, has a contract to deliver a large-scale plant in China and received private investments from a car manufacturer. Market interest from the chemicals sector is unknown but assumed limited due to the significant cost-premium and lack of market drivers.

Total Addressable Market 2

Low Carbon Competition: 3

Bio-based methanol is an established alternative, although availability of bio-feedstocks may limit its penetration. CCU olefins may compete with bio-based and recycled material routes.

Policy & Regulatory Factors: 3

No significant regulatory barriers identified. The chemicals sector has no dedicated support for CCU. The route is not cost competitive so lack of policy support could be a barrier.

Cost & Value Proposition: 2

The CCU route is not expected to reach cost-parity with fossil methanol, with best-case current costs being at least twice that of fossil methanol.

Scalability (Score: 3)

Policy & Regulatory Factors 3

Technical Deployment Factors: 3

A new plant is required but technology is modular and no significant engineering challenges are envisaged. The route requires large amounts of renewable electricity for hydrogen production, but this can be intermittent.

Current TRL: 4

CRI have a small-scale commercial plant in Iceland and pilot projects for specific applications.

TRL 8 | 4 kt/y Demonstration Plant (2015)

Energy Demand: 1

Green hydrogen production requires large amounts of low cost, renewable electricity.

High Energy Demand

Other Impacts (Score: 2)

Social & Environmental Impacts: 3

Benefits associated with lower use of fossil resources. However, additional impacts (good and bad) from large-scale renewable deployment.

Energy Demand 1

Water & Land Use: 1

Increased land and water use due to need for hydrogen production and renewables deployment.

(a) Bazzanella et Ausfelder 2017, Low carbon energy and feedstock for the European chemical industry. Technical study.
(b) Data is from the MMSA shared via the Methanol Institute, available here: https://www.methanol.org/methanol-price-supply-demand/
(c) MTO = Methanol to Olefins (a process for producing olefins from methanol rather than naphtha cracking)

Assessment Outcomes

- **CO_2 Mitigation Potential:** Several studies have concluded that methanol produced from CO_2 has a lower global warming impact than that produced from fossil sources if renewable electricity is used for water electrolysis[64,65,66]. Assuming that 1.53 t CO_2 is mitigated per tonne of methanol[51] (cradle-to-gate) then the total mitigation potential would be of the order of 120 MtCO_2/yr, if the entire existing market for methanol as a chemical or chemical intermediate (80 Mt / y)[44] were to adopt the CCU route.
- **Market Uptake Potential:** The market interest for CCU methanol from the chemicals sector is expected to be limited due to its lack of value proposition. Current estimates suggest that CCU methanol is at best-case twice the cost of fossil methanol[67,68], and there were no identified sustainability incentives within the sector that would justify such a cost premium. Therefore, further policy or regulatory support would be needed to enable market uptake. Furthermore, the existence of other sustainable production methods, such as bio-based routes, mean that CCU methanol has an established competitor for any sustainable methanol market that develops. One consideration for the long-term is that these competitive routes could be limited by the availability of biomass. It should be noted that CCU methanol is available to purchase in Europe (small-scale production from CRI) but that this CCU product is primarily marketed as a sustainable fuel.
- **Technical scalability:** The technology has a high TRL and no significant engineering challenges to its deployment are envisaged: it is modular and plants are similar to, or simpler than, conventional facilities[69]. The main identified constraint on deployment is the requirement for large amounts of low-cost, renewable electricity which could restrict the locations in which the technology can be deployed.
- **Other Impacts:** The use of CO_2 as the carbon source substitutes fossil carbon, with overall consumption of fossil resources reduced for the CCU route. This impact has associated environmental and social benefits. The CCU route is energy intensive requiring much higher energy input than the counterfactual, with difficult implications for the energy system. Furthermore, the requirement for large-scale renewables deployment for hydrogen generation has the impact of increasing land use and water consumption.

4.1.2 Formic Acid

Formic acid has a variety of small-scale end-uses with an approximate annual demand of 0.7 Mt per annum. Formic acid is used in agriculture for silage and animal feed (27%), leather and tanning applications (22%), pharmaceuticals & food chemicals (14%), as well as in the textile industry (9%) and for natural rubber production (7%)[70]. Formic acid is typically chosen for these applications due to its unique properties; being strongly acidic and a valuable reducing agent. This makes it unlikely that formic acid could be substituted with an alternative product. There is some interest in use of formic acid as a fuel for fuel cells, although this is in the proof-of-concept phase.

Formic acid is typically derived from crude oil. There are two main conventional processes for producing formic acid: via methyl formate hydrolysis and via acidolysis of alkali formates. The methyl formate hydrolysis process dominates with 80-90% of the installed capacity based on this method[71]. Around 70% of the climate change impact of this process is linked to the production of carbon monoxide from fuel oil, which is derived from crude oil. This is followed by the production of heat and electricity. The production process emits around 2 kg CO_2 per kg of formic acid produced[72].

[64] Artz et al. 2018, Sustainable Conversion of Carbon Dioxide: An Integrated Review of Catalysis and Life Cycle Assessment
[65] Pontzen et al. 2011, CO_2-based methanol and DME - Efficient technologies for industrial scale production
[66] Thonemann et al. 2020, Environmental impacts of CO_2-based chemical production: A systematic literature review and meta-analysis
[67] ECOFYS and Imperial College London 2017, Assessing The Potential Of CO_2 Utilisation In The UK (for BEIS). [LINK]
[68] Perez-Fortes et al. 2015, Methanol synthesis using captured CO_2 as raw material: TEA and Environmental Assessment [LINK]
[69] CRI 2018, Process Advantages of Direct CO_2 to Methanol Synthesis [LINK]
[70] Ullmann's Encyclopedia of Industrial Chemistry: Formic Acid, 2016
[71] Hietala et al. 2016, Formic Acid, In: Ullmann's Encyclopedia of Industrial Chemistry.
[72] Ahn et al. 2019, System-level analysis and life cycle assessment of CO_2 and fossil-based formic acid strategies.

Several CO_2 utilisation routes are of interest for formic acid production, with the catalytic hydrogenation route assessed here. Methods for obtaining formic acid from CO_2 include catalytic hydrogenation pathways, such as that described by Perez-Fotes et al. (2015)[74], electrochemical reduction pathways, such as those pursued by Det Norske Veritas and Mantra Venture Group, as well as photocatalytic routes. The focus of this analysis has been on the catalytic hydrogenation route which is at early stages of development, but is better understood compared to alternative routes.

CCU routes are more expensive than fossil production with costs dominated by catalysts costs. Costs for catalytic hydrogenation are estimated to be 2.5 times that of the conventional formic acid production[74]. The route associated with this estimate has a high consumption rate of a rare and expensive ruthenium-based catalyst, with the costs of catalyst replacement dominating the product costs. There is considerable uncertainty in this estimate, with laboratory catalyst costs likely used in the calculation, however the high price of ruthenium alone implies that catalyst costs would dominate. A range of other catalysts have been suggested in the literature[73], with further research necessary to improve catalyst lifetimes, selectivity, and affordability.

Emissions are lower than conventional routes if renewable electricity is used. Energy, land and water demands could be comparable. The conventional route to producing formic acid is emission-intensive, meaning that large emission reductions could be achieved with the CCU pathway. An optimistic study that assumed zero carbon electricity and steam reported that a cradle-to-gate CO_2-eq emission reduction of 92%[74] (approximately 2 tonnes of CO_2 avoided per tonne formic acid) could be achieved using the CCU route. Emission reductions will however vary with the source of electricity, CO_2 and hydrogen feedstocks used (as investigated in the parallel study Reality Check: CO_2 Hydrogenation).

[73] Álvarez et al. 2017, Challenges in the Greener Production of Formates/Formic Acid, Methanol, and DME by Heterogeneously Catalyzed CO_2 Hydrogenation Processes [LINK]

Assessment: Formic Acid (FA)

Sub-criteria score

Mitigation Potential (Score: 3)

Emissions Avoided[(a)]: 5

The counterfactual route is emission intensive. The CCU process results in significantly lower GHG emissions than the counterfactual route, with optimistic potential to avoid 2t CO_2 per tonne formic acid.

92% reduction

Cradle-to-gate GWP reduction cf. counterfactual

Total Addressable Market[(b)]: 1

The existing market size is small at approximately 1 Mt or less. There is some interest in the use of formic acid in fuel cells or as a hydrogen carrier, which would expand the market opportunity.

1 Mt / yr

Market Uptake Potential (Score: 2)

Commercial Development: 2

Limited Information. Patents for hydrogenation routes have been acquired by companies like BP and BASF.

Total Addressable Market 1

Low Carbon Competition: 5

Properties of FA mean that there is low risk of substitution with alternative chemicals. CCU is a low-carbon route to the produce the same chemical.

Policy & Regulatory Factors: 1

No significant regulatory barriers identified. The chemicals sector has limited support for CCU. The route is not cost competitive so lack of policy support could be a barrier.

Cost & Value Proposition: 2

The route is more expensive (approx. 2.5 times) than the conventional route.

Scalability (Score: 2)

Policy & Regulatory Factors 1

Technical Deployment Factors: 2

A new plant is required with novel engineering expected. The route requires access to renewable electricity. Some options require rare catalyst materials.

Current TRL: 1

Patents have been granted for the hydrogenation route, but further lab research is necessary. Route is not yet validated in relevant environment.

TRL 3 | Lab Research

Energy Demand: 3

CCU could be lower than that of the conventional route, if heating and cooling needs can be offset through integration.

Similar

Other Impacts (Score: 3)

Social & Environmental Impacts: 3

Limited Information.

Energy Demand 3

Water & Land Use: 3

Water and land use are similar to the fossil route.

(a) Perez-Fotes et al. 2015, Formic acid synthesis using CO2as raw material: TEA, environmental evaluation, and market potential
(b) GCI 2016, Global Roadmap for Implementing CO2 Utilisation

Assessment Outcomes

- **CO_2 Mitigation Potential:** The CCU process results in significantly lower GHG emissions than the counterfactual route, with optimistic claims of a 92% reduction in cradle-to-gate emissions (approximately 2 tonnes of CO_2 avoided per tonne formic acid) in emissions compared to the counterfactual route assuming zero carbon electricity and steam[74]. Despite this large percentage reduction, the total global mitigation potential is limited by the relatively small market demand (less than 1 Mt) for formic acid. Based on these values, if the entirety of the existing market converted to the CCU route then the total amount of CO_2 mitigated would be below 20 Mt per year.
- **Market Uptake Potential:** The CCU route currently lacks a value proposition that would drive demand within the chemicals sector: costs for catalytic hydrogenation are estimated to be 2.5 times that of the conventional formic acid production[74] and no sustainability incentives that would justify such a cost premium were identified in the chemicals sector. Therefore, further research - for example by improving the selectivity, lifetime, and affordability of catalysts - is necessary to drive cost reductions. In the context of a net-zero world, the CCU route may profit from the lack of alternative low carbon production or substitution options for formic acid. The acquisition of patents by companies like BP and BASF[74] could indicate future market potential for the routes.
- **Technical scalability:** The technology is at an early stage of development (TRL 3-5)[75]. meaning that further research, pilot demonstrations and large-scale demonstrations are first needed before the route could be deployed at global scale. Further potential barriers to at-scale global deployment are the requirement for low-cost, renewable electricity and the requirement of some routes for rare catalyst resources that may have restrictions placed on their use.
- **Other Impacts:** The energy demand for the CCU route[76] has the potential to be comparable to that of the methyl formate fossil route (6.61 MWh / t formic acid[77]) if energy demands for heating and cooling can be offset through integration. It is thought that water and land use will be similar to the fossil route.

4.1.3 Dimethyl Carbonate (DMC)

The global market for dimethyl carbonate (DMC) is approximately 90 kt with end-uses in polycarbonate production (50%) and use as a solvent (25%)[82]. DMC is an alkyl carbonate with the chemical formula $(CH_3O)_2CO$. It is often considered to be a 'green' reagent, being a biodegradable and non-toxic chemical. Currently DMC is mostly used as an intermediate in polycarbonate synthesis however its use as a solvent is growing, driven by its exemption from the volatile organic compounds classification in the US. DMC has many other potential uses, with possible future markets including use as a non-toxic methylating agent (substituting toxic dimethyl sulfate and phosgene) and as an octane boosting fuel additive (substituting MTBE).

The dominant commercial route for DMC production is the "Eni" process which uses CO, methanol and O_2 as feedstock. Two production routes used in the past for DMC were (1) the phosgenation of methanol and (2) the carbonylation of methanol via methyl nitrite. These routes were problematic with the first using high toxicity phosgene and the second having unstable intermediates among other issues[82]. They have since been surpassed by the "Eni" process which now dominates commercial production[82]. The "Eni" process involves the oxidative carbonylation of methanol, using carbon monoxide, methanol, and oxygen as feedstocks[82]. Several alternative routes are being developed, with opportunities to use CO_2 either directly or indirectly[82].

DMC can be produced from CO_2 via both direct and indirect utilisation routes. There are multiple CO_2 utilisation routes to arrive at dimethyl carbonate. Two routes considered here are outlined below.

[74] Perez-Fotes et al. 2015, Formic acid synthesis using CO_2as raw material: TEA, environmental evaluation, and market potential [LINK]
[75] ECOFYS and Imperial College London 2017, Assessing The Potential Of CO_2 Utilisation In The UK (for BEIS). [LINK]
[76] M. Pérez-Fortes and E. Tzimas, 2016, Techno-economic and environmental evaluation of CO_2 utilisation for fuel production. Synthesis of methanol and formic acid
[77] J. Sutter, 2011. Ecoinvent 3.6 dataset documentation: formic acid production, methyl formate route - RER,

- **Indirect - Transesterification of CO_2 derived cyclic carbonates[84]:** This route forms the initial step of an industrialized Asahi Kasei process. Ethylene carbonate is first produced via a reaction between CO_2 and ethylene oxide. It is then reacted with methanol to yield DMC and ethylene glycol. Developments are needed to optimize the final separation of the DMC product. The use of epoxides may be a potential concern due to their classification as carcinogenic.
- **Direct - Electrochemical reaction of CO_2 with methanol[82]:** This route involves the direct reaction of methanol and CO_2 via electrochemical reduction which is currently low TRL (lab research). Further research is needed to improve the conversion rate of reactants to DMC (increase yield) and reduce the energy consumption of the process.

Asahi Kasei have developed similar routes for the first step of polycarbonate production. The indirect route is used commercially as the first-step in the Asahi Kasei process to produce diphenyl carbonate from CO_2[78]. Asahi Kasei are also developing a route in which a dialkyl carbonate is produced from reactants of CO_2 and an alcohol[78]. As these steps are integrated within other chemical processes, the separation of DMC or dialkyl carbonate as a product is assumed to not be required. Therefore, although aspects of the above reactions may have been explored industrially, further work is needed to optimise yields and develop final separation processes.

The literature has variable conclusions regarding the extent to which the CO_2 utilisation routes may mitigate emissions. Determining the potential for CO_2 mitigation from the literature is challenging due to the differences in assessment boundaries used, differences in the conventional pathway assumed for comparison (phosgene, Eni, Bayer) and differences in overall conclusions. In general, the indirect route (ethylene carbonate transesterification) has been reported to have lower global warming impact than that of fossil-based DMC production, with emissions per tonne of DMC reported as between 0.45-0.77 t CO_2-eq (gate to gate)[81,84] and 0.86 t CO_2-eq (cradle to gate)[79]. Results from Kongpanna et al. suggest a 13% reduction in CO_2 emissions (gate-to-gate) corresponding to an avoidance of 0.07 kg CO_2-eq / kg DMC[81,82]. It is reported that at present the direct route (electrochemical reduction) results in a 2 to 3 times greater GWP than the counterfactual Eni process due to the low yields (0.7%) obtained and associated energy for separation (80% of GWP)[80]. This source however considers the route at its current low TRL and associates large proportions of emissions to energy generation. It is conceivable however that yields could be improved from further research and energy for the process could instead come from low carbon sources. The study does detail that a process yield of at least 20% is needed to reach party with the counterfactual, with yields of 30% and 50% expected to reduce emissions by 46% and 60% respectively[82].

[78] Asahi Kasei 2015, Press Release: Construction of validation plant for DRC process to produce DPC, a monomer of PC [LINK]
[79] Monteiro et al. 2009, Sustainability metrics for eco-technologies assessment, Part II. Life cycle analysis. [LINK]
[80] Garcia-Herrero et al. 2016, Environmental Assessment of Dimethyl Carbonate Production: Comparison of a Novel Electrosynthesis Route Utilizing CO_2 with a Commercial Oxidative Carbonylation Process [LINK]

Assessment: Dimethyl Carbonate (DMC)

Sub-criteria score

Mitigation Potential (Score: 3)

Emissions Avoided: 4
There are a wide range of values reported for GWP of both the CCU and conventional routes. Emission reductions are reported for the indirect route (ranging extents). At present the direct electrosynthesis route does not lead to emission reductions due to low yields and energy requirements.

Total Addressable Market[a]: 1
The current market for DMC lies in the production of polycarbonates (50%) and as use as a solvent (25%). Future markets include use as a non-toxic methylating agent (substituting toxic dimethyl sulfate and phosgene) and as an octane booster (fuel additive) substituting MTBE.

90 kt / yr
Todays existing market for DMC

Market Uptake Potential (Score: --)

Commercial Development:
Market interest for CCU DMC is unknown. Asahi Kasei developed an indirect CO_2 utilisation route that is used commercially, and is reportedly developing a direct utilisation route for dialkyl carbonates (which could include DMC). However, these routes are developed as the initial step for other reactions (e.g. BPA-PC).

Policy & Regulatory Factors:
No dedicated CCU policy/regulatory support was identified within the chemicals sector. This is not necessarily a barrier as the route has potential to develop without support, if added benefits are valued or if profitable (uncertain).

Total Addressable Market 1

Low Carbon Competition:
None known. Limited data.

Cost & Value Proposition[b]: 4
A TEA of the indirect route reported it to be profitable with a payback period of 5 years. The route also yields valuable by-products.

Scalability (Score: --)

Policy & Regulatory Factors

Technical Deployment Factors:
Limited information.

Current TRL:
Research is ongoing to optimize the final separation of DMC, improve yields and reduce energy consumption.

Energy Demand:
Current low-levels of development mean that there is a large energy requirement for product separation.

Higher Energy Demand

Other Impacts (Score: --)

Social & Environmental Impacts:
Limited information.

Energy Demand

Water & Land Use:
The process is expected to have increased land and water use.

(a) Garcia-Herrero et al. 2016, Environmental Assessment of Dimethyl Carbonate Production: Comparison of a Novel Electrosynthesis Route Utilizing CO2 with a Commercial Oxidative Carbonylation Process
(b) Souza et al. 2014, Production of DMC from CO2 via Indirect Route: Technical Economical Environmental Assessment

Some sub-criteria have not been scored due to a lack of information relevant to the applied scoring system.

Assessment Outcomes

- **CO_2 Mitigation Potential:** The literature has variable conclusions regarding the extent to which the CCU may mitigate emissions, if at all. Emission reductions of 13% (0.07 kg CO_2-eq / kg DMC) are reported for the indirect route[81] however this study only compares the production process and not the emissions associated with feedstocks (gate-to-gate system boundaries). At present the direct route results in a 2 to 3 times greater GWP than the counterfactual Eni process due to the low yields (0.7%) obtained and associated energy for separation (80% of GWP)[82]. A process yield of at least 20% is needed to reach party with the counterfactual, with yields of 30% and 50% expected to reduce emissions by 46% and 60% respectively[82]. The total mitigation potential resulting from any reductions achieved will be limited by the relatively small demand for DMC (90 kt / y) [82].
- **Market Uptake Potential:** There was limited information to guide the assessment of CCU DMC market uptake potential. It is understood that the indirect process is used as an initial step in a commercialised Asahi Kasei process[82], and that the company have developed a route similar to the direct process discussed here for the production of dialkyl carbonates from an alcohol and CO_2[83]. A TEA of the indirect route reported it to be profitable with a payback period of 5 years[84]. The route also yields the valuable by-product, ethylene glycol. In general, the chemicals sector does not have dedicated policy or regulatory support for CCU routes.
- **Technical scalability:** The authors understanding is that dedicated DMC production from CO_2 has not yet been deployed and that further lab-based research is needed to improve yields, optimise separation of products and reduce energy consumption. This low level of technology development, as well as the currently high energy requirements, could be a barrier preventing large scale deployment even if market interest in the route were to develop.
- **Other Impacts:** The literature has variable and contradictory conclusions regarding the additional environmental impacts of CCU DMC routes. It is thought that lifecycle water and land use are increased compared to the counterfactual.

4.2 Strengths, Weaknesses & Discussion (Chemicals)

The primary criteria results for CCU methanol and formic acid, which involved catalytic hydrogenation of CO_2, are shown in Figure 7. It was not possible to provide high-level scores for CCU dimethyl carbonate due to data gaps in the assessment. The routes assessed had adequate to low performance in most categories, implying that in general the use of CO_2 as a feedstock for chemicals has the potential to:

- **Achieve some level of emission mitigation:** These routes result in somewhat to significantly less GHG emissions per tonne and have small addressable markets. CO_2 sequestration is temporary (<10 years).
- **Receive limited market demand:** There is some interest in developing CCU routes, however there is currently a lack of market drivers for uptake.
- **Scale production with conditions:** Technologies could be deployed in appropriate locations (access to renewables, water) at scale, but some routes need further RD&D.
- **Have adverse impacts:** Deployment of technologies could adversely impact energy systems and use of resources (land, water, catalyst materials).

---

[81] Kongpanna et al. 2015, Techno-economic evaluation of different CO_2-based processes for dimethyl carbonate production [LINK]
[82] Garcia-Herrero et al. 2016, Environmental Assessment of Dimethyl Carbonate Production: Comparison of a Novel Electrosynthesis Route Utilizing CO_2 with a Commercial Oxidative Carbonylation Process [LINK]
[83] Asahi Kasei Corp. 2017, Press Release: Demonstration of validation plant for DRC process to produce DPC, a monomer of PC [LINK]
[84] Souza et al. 2014, Production of DMC from CO_2 via Indirect Route: Technical Economical Environmental Assessment [LINK]

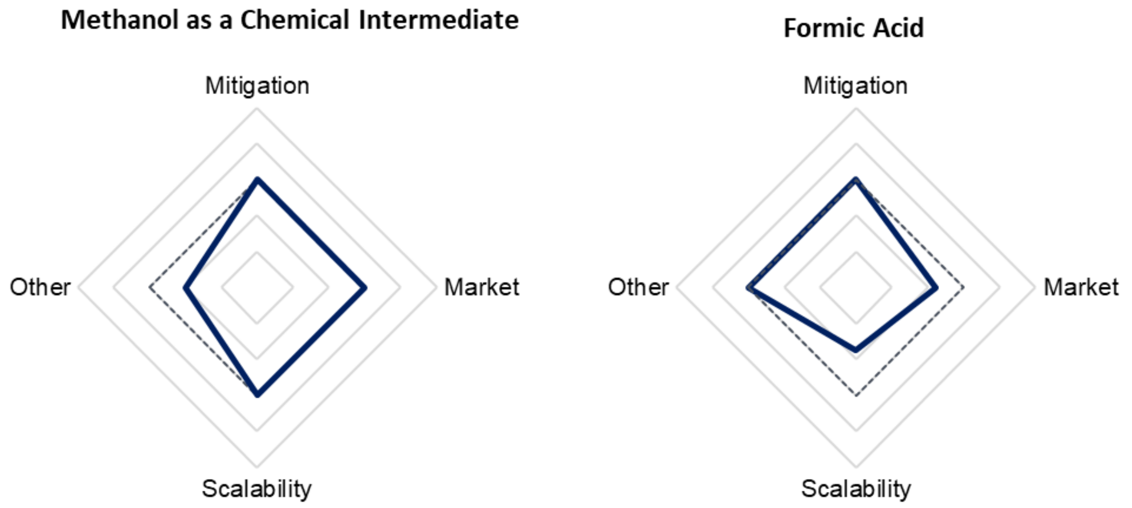


Figure 7: Radar plot of primary criteria scores (1-5) for **chemicals,** with higher scores indicating an area of strength. The approach to scoring is detailed in Section 2.2 of this report and follows a comparative approach between all commodities investigated. **Mitigation:** The ability of the CCU route to lead to emissions abatement in the future, if there are no technology or economic barriers. **Market:** The ability of the CCU route to have an established future market in a low-carbon world, if there are no technology barriers. **Scalability:** The ability of the CCU route to deploy globally or at a large scale, if there is significant market demand. **Other:** The extent to which any additional impacts resulting from CCU deployment are beneficial (high score) or detrimental (low score).

Common strengths for the routes were emissions avoidance (per tonne) and a lack of established low carbon alternatives. If low-carbon electricity is used, then hydrogenation routes offer reductions in lifecycle emissions by the avoidance of upstream fossil-emissions and the recycling of captured CO_2. There are limited low-carbon alternative routes for producing carbon containing chemicals at scale, implying that CCU chemicals could receive market interest under strong net-zero world ambitions.

'Cost and Value Proposition' and 'Policy and Regulatory Factors' were identified as key areas of weakness to be improved upon. The routes are more expensive than the conventional production route and within the chemicals market this is a significant barrier for market demand. There is a lack of dedicated policy or regulatory support for low carbon chemicals. Policy support is required to achieve successful market uptake.

High energy demand was identified as a key limitation, with impacts on technical scalability and other impacts. The hydrogenation routes require high levels of dedicated low-carbon electricity supply, the availability and costs of which is expected to vary by region. The use of this resource for CCU chemicals could have adverse impacts on local energy systems, if electricity is also needed for other decarbonization in the region. Therefore, there are restrictions on where technologies could be deployed, impacting the potential scalability of the routes. Furthermore, water resources are required for the hydrogenation routes and the deployment of renewables can result in increased land-use. In the case of methanol, overall energy demand is expected to increase significantly.

Between the routes, there are key differences in CO_2 **utilisation techniques and the level of technology development, as well as the addressable market size.** Methanol and formic acid routes convert CO_2 into a C1 building block by reaction with hydrogen, whereas the DMC route incorporates CO_2 as a carbonate group. CCU methanol has a higher TRL than formic acid and DMC, with the former having been demonstrated at industrial scale whist the latter require further lab-based research. Therefore, in the near-term methanol has greater potential to be deployed at scale. Although all routes have relatively small market sizes, the market for methanol as a chemical (80 Mt) is much greater than the markets for formic acid (< 1 Mt) and DMC (< 0.1 Mt).

There were evidence gaps and uncertainties when assessing lifecycle environmental impacts. There were a lack of LCA studies for the routes investigated and within those found there was a lack of data on the scope used. Results vary a lot for different technologies to produce the same product. The most advanced LCA work was found to be on hydrogenation of CO_2 to produce methanol.

Regional Considerations

Petrochemicals are a highly traded commodity, more so further down the value chain. There are many points along the value chain in which trade can occur, with derivative chemicals tending to be traded more than primary chemicals due to their higher value and often easier transportation[41]. The distinction between importers and exporters of the largest volume petrochemicals and their derivatives has remained fairly consistent in the last few decades[41].

For conventional petrochemicals, feedstock availability (and thus costs) are the most influential factor in determining regional production advantages. Feedstock costs can account for between 15-85% of the production costs for higher value chemicals, varying with the type of feedstock used[41]. North America and the Middle East have the lowest cost feedstocks resulting in competitive production, whilst China and Europe have higher cost feedstocks. Declining oil prices can narrow the gap between regional feedstock costs. Figure 8 shows the regional variation in petrochemical feedstocks and how the average costs vary by region.

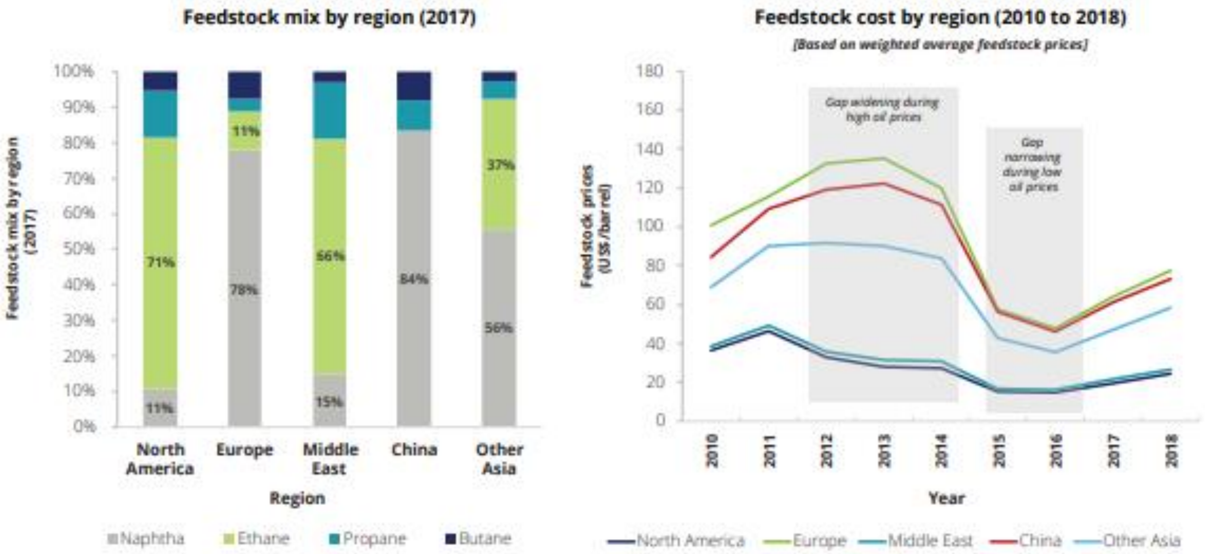


Figure 8: Regional trends in petrochemical feedstock mix and costs. Taken from: Deloitte 2019, The Future of Petrochemicals[85]. With original source being: Deloitte Development LLC analysis based on data from Krungsri Research and Bloomberg Intelligence, accessed in February 2019.

CCU production and consumption could be disconnected. The highly traded nature of chemicals means that, like with existing supply and demand patterns, the production and consumption of CCU chemical products would not necessarily occur within the same region. Therefore, when thinking about opportunities for CCU it might be important to consider drivers for consumption and production separately.

CCU methanol and formic acid would be cheaper to produce in regions with low-cost renewable electricity. The costs of CCU methanol and formic acid are highly dependent on the costs of electricity, with renewable electricity assumed to be required to obtain the true CO_2 mitigation benefits (a key driver for the routes). Therefore, production of these chemicals could be favoured in regions with low-cost and high availability of renewable electricity, such as the Middle East and North America.

[85] Deloitte 2019, The Future of Petrochemicals [LINK]

Demand for CCU chemicals is likely to be highest in regions with strong climate policies… CCU routes for methanol and formic acid are much more expensive than their counterfactuals whilst having no added-value in terms of practical product performance. Their main market driver is their sustainability compared to conventional chemicals. The value of this benefit is only likely to be economically realised in a region with strong climate ambition and suitable policies to support lower emission or more sustainable products. The lack of low-carbon alternatives for chemicals and eventual end-of-life emissions, could mean that in the long-term CCU chemical routes may be of particular interest for regions with net-zero ambitions, such as Europe.

…Or in regions where counterfactual costs are high. Although the costs of the CCU routes for methanol and formic acid are high, there are regions where costs of counterfactual products may be much higher than global averages, perhaps due to a lack of local fossil reserves or a reliance on imports (Europe, China). This could allow CCU chemicals to be seen as more competitive in those regions, particularly if combined with other drivers.

RD&D, Evidence Gaps & Uncertainties

Based on available data, the assessment concluded that the catalyst costs for formic acid are prohibitively high, leading to a significant cost premium. However these costs may reflect a reality in which these catalysts are currently only produced/purchased on a lab-scale, and therefore could contain significant uncertainty with regards to their costs when scaled up. If costs are however indicative of at-scale production, development of lower cost catalysts with a longer operational lifetime could improve cost-competitiveness to a degree. Alternative catalysts have been identified, and so there remains scope to for investigation.

For the direct route to producing DMC from CO_2, studies highlighted the need to increase the yield of the process. This could be achieved through further research on alternative materials for the electrodes and ionic liquids as well as scaling up and optimization of operating conditions. For the indirect route, the separation of the DMC and methanol is yet to be properly considered.

Although olefins can be produced from methanol via methanol-to-olefins, research is ongoing to develop a direct conversion pathway. Within this, the production of catalysts is challenging from economic and environmental points of view. For instance, the production of zeolites needs large amounts of energy, high pressures and long reaction times. Current research is looking into producing zeolites more efficiently and in more environmentally-friendly ways, for instance by organic-template-free, ionothermal, solvent-free and microwave synthesis[86].

[86] Li, Y., Li, L., and Yu, J. (2017) Applications of zeolites in sustainable chemistry. Chem, 3 (6), 928–949.

5 Polymers

Polymers are used for the manufacture of plastics, with the most common polymers being polyethylene and polypropylene, used in the production of plastic bags, packaging, and bottles. Aside from the well-known disposable consumer end-uses, plastics are also key materials within automotive, construction, manufacturing and electronics industries. Most polymers are conventionally derived from fossil resources via intermediate chemical products. A limited number of market players dominate production. In Europe and North America the polymer market tends to be consolidated with a few key players dominating production capacity in each region.

This chapter focuses on polycarbonates and polyols. Polycarbonate is used as an engineering thermoplastic in a broad range of applications such as car manufacturing, DVDs, optical lenses, and construction[87]. Polyols are mainly used in the production of rigid and flexible foams (polyurethane foams), with other end-uses in coatings, adhesives, sealants, and elastomers. Polyurethane has dominant end uses in construction, furniture, and automotive components.

5.1 CO_2 Utilisation Opportunities (Polymers)

A potential CO_2 utilisation route in the polymers sector is the direct insertion of CO_2 **molecules into polymer backbones** via their polymerisation with a range of epoxides or diols. This route avoids the energy-intensive cleavage of C=O bonds that is required in other utilisation routes and has gained increasing attention during the past few decades. In particular, there has been commercial interest in the production of polycarbonate and poly(ether carbonate) polyols as outlined below. Whereas polycarbonate from CO_2 is expected to directly substitute existing polycarbonate end-uses, poly(ether carbonate) polyols are being investigated as an alternative for conventional polyols (different chemical structure). Production of polyurethane foams from these new CO_2 incorporating polyols is of particular interest.

5.1.1 Polycarbonate

Bisphenol-A-based polycarbonates (BPA-PC) are a common class of engineering thermoplastic used in a broad range of applications such as car manufacturing, DVDs, optical lenses, and construction[88]. Demand for polycarbonates was 4.1 Mt in 2017[88] with five industry players accounting for 81%[89] of production capacity. These polycarbonates are conventionally produced using highly toxic phosgene as a reactant and methylene chloride, a suspected carcinogen, as a solvent[88].

An alternative route that utilises CO_2 as a replacement feedstock for phosgene and avoids the need for chlorinated compounds was developed by Asahi Kasei (Japan)[90]. This route has several advantages over the conventional route: it is less material- and energy- intensive and there are no waste products thereby eliminating expensive purification steps[88,90]. It is also claimed by the developers that the route has economic benefits for both plant construction and feedstock costs and that the route reduces CO_2 emissions by 0.173t CO_2 per tonne of polycarbonate[90]. The boundaries of this assessment however are not specified and the value equates instead to the quantity of CO_2 that is sequestered per tonne.

Asahi Kasei commercialised the process in 2002 with a 50 kt/y plant in Taiwan (now 150 kt/y)[90]. The company licenses the technology openly and expected its technology to achieve a 25% market share[90]. Six companies had licensed the technology by 2018 with plants operational or under construction in Russia, South Korea, and Saudi Arabia and a total CCU polycarbonate production capacity of 1.07 Mt expected by 2019[91].

[87] Kamphuis et al., 2019. CO_2-fixation into cyclic and polymeric carbonates: principles and applications. Green Chemistry. [LINK]
[88] Kamphuis et al., 2019. CO_2-fixation into cyclic and polymeric carbonates: principles and applications. Green Chemistry. [LINK]
[89] Covestro Investor Presentation, June 2018
[90] Fukuoka et al., 2007. Green and sustainable chemistry in practice: Development and industrialization of a novel process for polycarbonate production from CO_2 without using phosgene. Polymer Journal. [LINK]
[91] Qian Zhu (IEACCC) 2019. Developments on CO_2-utilization technologies. [LINK]

Assessment: Polycarbonate (BPA-PC)

Sub-criteria score

Mitigation Potential (Score: 3)

Emissions Avoided[(a)]: 4

Developers claim that the route reduces CO_2 emissions by 0.173t CO_2 per tonne of polycarbonate, however a life-cycle assessment was not identified. This value likely equates to the quantity of CO_2 that is utilised per tonne.

Total Addressable Market[(b)]: 1

The CCU product is a direct substitute for existing polycarbonate, a common engineering thermoplastic. The global demand for polycarbonate was 4 Mt in 2017 with growth projected.

4 Mt / yr

Market Uptake Potential (Score: 3)

Commercial Development[(a)]: 4

Six companies had licensed the technology (developed by Asahi Kasei) by 2018 with multiple plants operational or under construction. Developers expected that the technology could take a 25% share of the market, however the market is dominated by 5 key players each using conventional routes.

Technology Licensed | Adopted by small players

Policy & Regulatory Factors: 5

No significant barriers. No dedicated support. The route is cost competitive so could scale without support.

Total Addressable Market 1

Low Carbon Competition: 3

Bio-based and recycled polymers may compete with CCU polymers.

Cost & Value Proposition: 4

It is claimed that the route has economic benefits for both plant costs and feedstock costs. The process has several other advantages over the conventional route which may offer additional value proposition.

Scalability (Score: 4)

Policy & Regulatory Factors 5

Technical Deployment Factors: 3

Construction of a new plant is required however no significant engineering challenges are envisaged. CCU facilities could be easier to deploy than conventional facilities - e.g. due to permitting requirements.

Current TRL: 5

150kt plant operational since 2002 in Taiwan. Plants in Russia, Korea and Middle East.

TRL 9 | Operational Industrial Scale Plants

Energy Demand: 4

Developers claim energy savings over the conventional route due to high yields and improved selectivity.

Lower Energy Demand

Other Impacts (Score: 5)

Social & Environmental Impacts: 5

The route avoids the use of toxic reagents (phosgene, CH_2Cl_2) making it a safer process. All intermediates are recycled leaving no waste products and no need for waste water treatment.

Energy Demand 4

Water & Land Use:

Limited data.

(a) Fukuoka et al., 2007. Green and sustainable chemistry in practice: Development and industrialization of a novel process for polycarbonate production from CO2 without using phosgene.
(b) Kamphuis et al., 2019. CO2-fixation into cyclic and polymeric carbonates: principles and applications.

Some sub-criteria have not been scored due to a lack of information relevant to the applied scoring system.

Assessment Outcomes

- **CO_2 Mitigation Potential:** It is thought that the CCU route can lower emissions compared to the counterfactual route, although this is based on claims by the developers with no LCAs having been found. The total mitigation potential is limited by the small addressable market size for polycarbonates. If the entire existing market were to adopt the CCU route, then based on the developer value reported, a total mitigation of the order of 0.7 Mt of CO_2-eq per year could be achieved.
- **Market Uptake Potential:** The CCU technologies are commercially available under license from the developers and there is evidence of a business case for their adoption due to economic advantages and additional value propositions, such as higher purity product and avoidance of hazardous reagents. An important consideration is that the market size is small with existing production capacity dominated by a few key players that are experienced with their own production routes. This may act either as a barrier or an enabler to market uptake, dependent upon the respective company's interest in CO_2 utilisation. Opportunities for market uptake could lie in regions where production capacity is more fragmented, such as the Asian market. Indeed, the Asahi Kasei process has been deployed in Taiwan, Russia, South Korea, and Saudi Arabia.
- **Technical scalability:** No significant technical barriers or constraints to at-scale deployment were identified. However, use of the CCU technology would require construction of a new chemical plant as, unlike some other routes assessed in this study, the technology is not suitable for retrofit or containerised deployment. It is envisaged that engineering requirements could be similar to or simpler than the construction of conventional production facilities.
- **Other Impacts:** The route has the significant advantage of avoiding the hazardous reagents of phosgene and methylene chloride, therefore making it a safer process than he conventional route. In addition, the developers claim that the route is less material- and energy- intensive than the conventional route and that there are no waste products, eliminating expensive purification steps. The route also avoids potential chlorine impurities in the product which otherwise may lead to corrosion of subsequent processing equipment.

5.1.2 Polyols for polyurethane

Polyurethanes (PUR) are an important class of polymer that are used in the production of flexible and rigid foams, coatings, adhesives, sealants, and elastomers. Flexible PUR foams are found in furniture, automotive seating, sound insulation and footwear, whereas rigid PUR foams are used in the construction and automotive industry[88]. These foams are produced from the reaction of polyols, conventionally polyether or polyester polyols, and isocyanates, with properties dependent upon choice of polyol and isocyanate molecules[88]. In 2017 the market for polyether polyols for use in polyurethane was approximately 12 Mt, whilst the total market for PUR is reported as 20 Mt per year with growth projected[89,92].

Poly(ether carbonate) polyols produced using CO_2 as a feedstock are being investigated as alternatives to conventional polyols for the production of polyurethane. In these polyols, a CO_2 molecule acts as a partial substitute for fossil-based epoxide feedstocks and is incorporated into the polyol backbone via co-polymerisation with epoxides. It is reported that CO_2-epoxide based polyols can share similarities with both polyether and polyester based polyols, incorporating the good mechanical properties associated with polyether polyols and the good hydrolysis resistance associated with polyester polyols[88]. It is also claimed that these polyols and subsequent PUR foams have improved flame resistance compared to conventional products[88]. The CO_2 content can be tuned for different material properties up to 50% by weight[98]. However for use in flexible or rigid PUR foams the maximum CO_2 content is limited to 30% and 16% of the polyol weight respectively [93].

[92] Green Chem. 2014. Carbon dioxide as sustainable feedstock for polyurethane production [LINK]
[93] Von der Assen, 2015. Environmental potential of carbon dioxide utilization in the polyurethane supply chain [LINK]

CO_2 based polyols for use in polyurethane are being developed and trialled by several companies, including established market players. Covestro, formerly Bayer Material Science, has commercialised its CO_2-based polyol, branded Cardyon, for sale in Europe with a small production facility (5 kt per year) operational in Dormagen, Germany since 2016[91]. In 2017 Covestro was the second largest producer of conventional polyether polyols for polyurethane foam[89]. Saudi Aramco offers two types of CO_2 based polyols[94] (40 wt% CO_2 and 20 wt% CO_2), branded as Converge polyols, which it acquired from original developers Novomer, based in the USA. There are multiple other institutions developing and using catalyst technologies for the co-polymerisation of CO_2 and epoxides, including several developers based in China[91].

Market interest exists for the use of CO_2 based polyols in commercial products, including mattresses, sports flooring, and vehicle components. Cardyon polyols have been used in foam mattresses and furniture upholstery, with additional applications including sports flooring and car interiors[95]. Converge polyols have undergone commercial scale trials for rigid foam production and have been tested by Ford automakers for use in vehicle components[91]. In addition to reductions in carbon footprint compared to conventional polyols, it is claimed that CO_2 based polyols can offer superior properties at lower or competitive costs when produced at scale.

Use of CO_2 as a feedstock in polyol production lowers consumption of energy-intensive epoxide feedstocks and allows temporary sequestration of CO_2. It is reported that direct utilisation of CO_2 in polyols (by co-polymerisation with epoxides) can reduce the global warming potential of a product by up to 4 kg CO_2 for each kilogram of CO_2 used[93] and that utilisation of CO_2 at 20% by weight results in an 11-19% reduction in emissions compared to polyether polyols (cradle-to-gate)[96]. These reductions result primarily from the substitution of emissions-intensive epoxides with CO_2, accounting for 72% of the reduction, with the remainder resulting from CO_2 capture effects. An associated reduction in use of fossil resources of between 13-16% is also reported[96].

[94] https://www.aramco.com/en/creating-value/products/chemicals/converge [accessed: December 2020]
[95] https://solutions.covestro.com/en/brands/cardyon [accessed: December 2020]
[96] Von der Assen, 2014. Life cycle assessment of polyols for polyurethane production using CO_2 as feedstock: insights from an industrial case study [LINK]

Assessment: Polyols for Polyurethane

Sub-criteria score

Mitigation Potential (Score: 3)

Emissions Avoided[a,b]: 4

Emission reductions result primarily from reduced consumption of epoxide feedstock, as well as temporary sequestration of captured CO_2. Up to 4 kg of CO_2 can be avoided per kilogram of CO_2 utilized (cradle-to-gate).

11-19 % reduction

Cradle-to-gate GWP reduction cf. counterfactual for polyol of 20wt% CO_2.

Total Addressable Market[c]: 2

CCU polyols are a potential alternative to polyether polyols in the production of PUR. In 2017 the global production capacity for these polyols was 12 Mt with growth projected. The PUR market is estimated at 20 Mt with end-uses split across flexible and rigid foams, coatings, and adhesives.

12 Mt / yr

Market Uptake Potential (Score: 4)

Commercial Development: 4

CCU polyols developed by Covestro (a top player in the existing market) can be purchased in Europe. Saudi Aramco markets two CCU polyol products. Interest exists from automakers for use of these polyols in car interiors. Applications in mattresses and furniture are commercialized.

Large Companies – Existing Market Players

Total Addressable Market 2

Low Carbon Competition: 3

Bio-based and recycled polymers may compete with CCU polymers.

Policy & Regulatory Factors: 5

No significant barriers. No dedicated support. The route is cost competitive so could scale without support. CCU polyols must be tested to ensure their suitability for specific applications, however testing is common for new products.

Cost & Value Proposition[d]: 4

Claims that CCU polyols offer superior properties at lower or competitive costs when produced at scale. Potential cost savings of 15-30% from the partial replacement of epoxide feedstocks with less expensive CO2 feedstock.

Scalability (Score: 4)

Policy & Regulatory Factors 5

Current TRL: 4

Technology is being demonstrated at small scale in Europe and for product trials in the USA.

TRL 8-9 | 5 kt Demonstration Plant

Technical Deployment Factors: 4

Processes used are very similar to that of existing facilities. For low molecular weight polyols, it may be possible to use existing production facilities with minimal retrofit. Higher molecular weight polyols may require new facilities.

Energy Demand: 4

Energy reductions possible, dependent upon the balance between energy for CO_2 capture and for the epoxide feedstock.

Lower Energy Demand

Other Impacts (Score: 3)

Social & Environmental Impacts[a]: 4

A reduction in the use of fossil resources of between 13-16% is reported, with other environmental impacts being similar to the conventional route.

Energy Demand 4

Water & Land Use: 2

Potential increase in land-use requirements, with water consumption remaining similar.

(a) Von der Assen, 2014. Life cycle assessment of polyols for polyurethane production using CO_2 as feedstock: insights from an industrial case study.
(b) Von der Assen, 2015. Environmental potential of carbon dioxide utilization in the polyurethane supply chain
(c) Covestro Capital Markets Day 2018 - Investor Presentation
(d) ECOFYS 2017, Assessing the potential of CO_2 utilisation in the UK

Assessment Outcomes

- **CO_2 Mitigation Potential:** An LCA study has shown that a typical CCU polyol containing 20% CO_2 by mass can have a cradle-to-gate global warming potential that is 11-19% lower than a conventional polyether polyol, equivalent to a reduction of 0.4-0.6 tonnes of CO_2-eq per tonne of polyol[96]. Another study calculated that between 3.7-4.1 kg of CO_2-eq can be avoided per kilogram of CO_2 utilised (cradle-to-gate): achieved through CO_2 capture (0-0.84 kg CO_2-eq) and substitution of emission intensive epoxides (3.1 kg CO_2-eq)[93]. The total mitigation potential is limited by the addressable market size for polyols. If the entire existing market were to adopt the CCU route, then a total mitigation of the order of 6 Mt of CO_2-eq per year could be possible[97].
- **Market Uptake Potential:** CCU technologies are being developed by multiple companies and institutions across several global regions, with products available commercially[88]. Technology owners include large, well established chemical companies and key players in the existing market. It could be expected that the existing resources, RD&D facilities, and loyal customer bases associated with such companies could facilitate market uptake of the CCU route. Market uptake of the route could also be driven by the route's value proposition: it is claimed that CCU polyols can be cost-competitive with existing polyols and may offer superior properties in some cases[88,91]. There is evidence of market interest. For example, an automaker has previously trialled CCU polyols for use in vehicle interiors, with intentions to introduce the material to production lines by 2021[91]. A factor that may limit market uptake is the existence of competing low-carbon or sustainable alternatives such as bio-based polymers and recycled polymers[98]. Furthermore, the CCU product is not a direct substitute for existing polyether polys but rather a 'near drop-in' with differing properties. Therefore, product testing is required to ensure suitability for specific applications, and the acceptability of the product is likely to vary between applications[98].
- **Technical scalability:** No significant technical barriers or constraints to at-scale deployment were identified: the CCU route is thought to use processes that are well known to the industry today[98]. Some developers even claim that the CCU technology could be used at existing facilities via retrofit[98]. The CCU technologies are themselves considered to be at a high technology readiness level, however RD&D is ongoing to demonstrate applicability of CCU products for specific applications. Anecdotal evidence suggests that testing capacity within the market could limit the rate of scale-up.
- **Other Impacts:** Environmental benefits occur from the partial displacement of fossil-based epoxide feedstocks with CO_2. A reduction in use of fossil resources of between 13-16% is reported[96]. There is evidence to suggest that the CCU route has similar or lower energy demands compared to the counterfactual. Land use is expected to be greater.

5.2 Strengths, Weaknesses & Discussion (Polymers)

The primary criteria results for the assessed routes, which involved incorporation of CO_2 as carbonates in polymers, are shown in Figure 9. The routes performed adequately well in all categories, implying that the use of CO_2 as a feedstock for polymers has the potential to:

- **Achieve some level of emission mitigation:** These routes result in somewhat less GHG emissions per tonne. The routes also offer temporary CO_2 sequestration (<100 years).
- **Receive good market demand:** These routes have high commercial development, and a potential business case with minimal barriers.
- **Effectively scale production:** There are minimal technical barriers to deployment at-scale. The technologies are well developed, with existing demonstration projects or licensed technologies, and the routes do not require significant additional energy demands.

[97] Assumes a polyol of 20wt% CO_2 for all applications (simplification) and market size of 12 Mt per annum.
[98] ECOFYS and Imperial College London 2017, Assessing The Potential Of CO_2 Utilisation In The UK. [LINK]

- **Realise additional positive impacts:** Most of the additional impacts in terms of energy, land & water, and social & environmental impacts were beneficial.

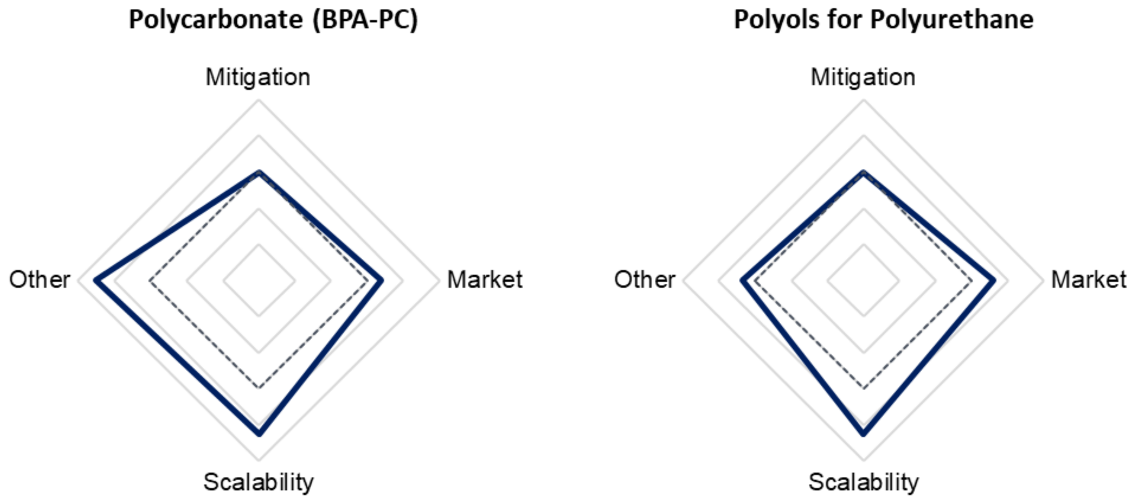


Figure 9: Radar plot of primary criteria scores (1-5) for **polymers,** with higher scores indicating an area of strength. The approach to scoring is detailed in Section 2.2 of this report and follows a comparative approach between all commodities investigated. **Mitigation:** The ability of the CCU route to lead to emissions abatement in the future, if there are no technology or economic barriers. **Market:** The ability of the CCU route to have an established future market in a low-carbon world, if there are no technology barriers. **Scalability:** The ability of the CCU route to deploy globally or at a large scale, if there is significant market demand. **Other:** The extent to which any additional impacts resulting from CCU deployment are beneficial (high score) or detrimental (low score).

CCU polycarbonate and polyols for polyurethane have strengths in 'market uptake potential': The CCU routes have a value proposition in that they have the potential to offer cost savings due to the use of lower cost feedstocks or being a more efficient process. The technologies are being developed by established companies that are key players in the market. For polyols there is evidence of market interest in the product with several applications tested and for polycarbonate the technology has been licensed by the developer to other players. There may in future be some competition from other low-carbon routes such as recycled or bio-based polymers, but these are not yet well established and may be constrained. The market is growing providing opportunities for new, innovative processes.

No significant technical barriers to deployment at a global scale were identified. The technologies are well developed and use a similar approach to existing production practices, meaning that scale-up and deployment would be similar to deploying facilities for the conventional route. In some cases it could be possible to retrofit existing production facilities. A limitation in the case of polyols is that the product is different to the conventional product, meaning that more testing is required and down-stream processes may need to adapt to accommodate new properties in processing. This however is not thought to be a significant barrier, and there may be potential to tune properties with percentage CO_2 content.

An area of weakness is the limited market size which restricts the overall mitigation potential. On a per tonne basis both routes lead to somewhat less emissions compared to their counterfactuals, however the potential impact of this in mitigating emissions is limited by the relatively small market sizes for both of these commodities.

Regional Considerations

There is a global spread in CO_2 utilisation developers targeting the sector. CO_2 utilisation routes for polyols, using polyether carbonates as alternatives to polyether polyols, have been developed both in Europe by Covestro with RWTH Aachen University, and in the United States by Novomer. Demonstration facilities have been built in both regions with testing for applications in different products. In Asia, the Japanese chemical company Asahi Kasei uses CO_2 as a feedstock for its polycarbonate production process. Therefore, CO_2 utilisation opportunities are not limited to a single region or market.

Strong climate ambitions could be an enabler for CCU polymers but are not essential. Regions with strong climate ambitions, such as Europe, could have greater interest in CO_2 utilisation for polymer production in general, due to the lack of alternative fossil-avoiding routes. However, the specific routes investigated here still use fossil feedstocks to an extent so this might not be as relevant. In regions without climate ambitions, the CCU routes could still gain market interest due to drivers on cost or feedstock efficiencies.

There may be less market interest for CCU polymers in regions with high oil and gas reserves. The feedstocks for conventional polymer production are likely to be lower in cost and have higher accessibility in regions with significant oil and gas reserves, such as the Middle East or North America. Any cost benefit from substituting fossil feedstocks with CO_2 would therefore become less significant. These regions may also have low motivations to reduce fossil consumption.

RD&D, Evidence Gaps & Uncertainties

A possible area for further investigation could be to reduce the viscosity of CO_2-based polycarbonates, currently higher than for the counterfactual polycarbonates, which limits their application in some areas[99].

There were evidence gaps and uncertainties when assessing lifecycle environmental impacts, including assessment of emissions, energy, water, and land use.

[99] Zhu, Q. (2019), Developments on CO_2-utilization technologies, Clean Energy, 3(2), pp. 85–100.

6 Fuels

The combustion of fossil fuels for provision of energy is the greatest source of anthropogenic CO_2 emissions. Fuels derived from natural gas, coal, and crude oil (fossil fuels) have major end-uses as a primary energy source in power generation, transport (road, marine, aviation) and heating (industrial, domestic). These fuels are mostly carbon atoms by weight and their combustion results in significant CO_2 emissions – up to 3.1 tonnes of CO_2 per tonne of hydrocarbon. They are the dominant end-use for extracted fossil-resources, with use of oil and natural gas for petrochemical feedstocks (non-fuels) accounting for only 14% and 8% of total primary demand respectively[41].

Low carbon alternatives now exist for each major end-use. Increasing efforts to drastically reduce emissions means that there now well-established alternatives to many of the current end-uses of fossil fuels. Power generation is being decarbonised by switching to renewables (wind, solar, geothermal, hydroelectric etc.), nuclear power, combustion of alternatives such as biomass or waste, and by retrofitting carbon capture to existing power stations. Transport is being decarbonised using electric vehicles, hydrogen fuel-cell electric vehicles, and biofuels. Plans to decarbonise heating include fuel-switching to electricity, hydrogen, and biomass, or retrofitting carbon capture at existing industrial sites.

There are many country or regional level regulations and incentives to support a reduction in the emission intensity of fuels, particularly transport fuels and industrial combustion. For road transport fuels specifically, these include:

- Mandates requiring a certain percentage of supplied fuels to be from a sustainable/renewable source or from biofuels specifically, an example being the EU Renewable Energy Directive. These may also include blending requirements for specific fuels.
- Fuel standards specifying a declining maximum carbon intensity for fuels, such as the California Low Carbon Fuel Standard.
- Government targets to phase-out diesel and gasoline vehicles by a specific date, accompanied by support for alternatives such as investment in electric vehicle charging infrastructure.

In the industry sector, incentives to reduce emissions from combustion of fuels may be in the form of a carbon pricing mechanism, such as a carbon tax or cap-and-trade system, or through funding support schemes or various other political / regulatory mechanisms. There are also incentives to increase efficiency in the use of fuels and reduce consumption.

CCU synthetic fuels may have potential in niche areas where decarbonisation is challenging. The Sustainable Development Scenario in the International Energy Agency's Energy Technology Perspectives 2020[100] report projects synthetic fuels to be a long-term abatement option for medium- and heavy-duty freight trucks and aircraft, entering these markets in the late 2020s. The present-day market demand for fossil based middle distillate hydrocarbons in these segments is roughly 580 Mt for freight trucks and 323 Mt for aviation fuels. The IEA's projections indicate that in the long-term (2070) synthetic fuels could meet around 3% and 40% of these markets respectively. The report projects a total annual demand for synthetic fuels of 254 Mt in 2070. In addition to these end-uses, synthetic fuels in the form of methanol or its derivatives are also thought to be a potential option for the marine transport sector. In the near term, synthetic fuels could be used as a temporary drop-in solution to allow continued value realization from existing assets.

[100] IEA 2020, Energy Technology Perspectives [LINK]

6.1 CO_2 Utilisation Opportunities (Fuels)

The most advanced CO_2 utilisation routes within the sector involve the reaction of CO_2 **with green hydrogen.** The fuels discussed here are built up solely from the feedstocks of CO_2 and either hydrogen or water. This is achieved via electrochemical reduction or catalytic hydrogenation reactions. A large variety of fuels can be developed, particularly considering methanol is a conventional feedstock for other fuels such as DME. Due to the requirements for hydrogen as a feedstock, the routes are energy intensive and require large amounts of low-carbon electricity. The costs and emissions are highly dependent upon the electricity source.

The CO_2 acts as an alternative to fossil-based carbon sources. Sequestration time is short with utilised CO_2 **emitted on combustion.** CO_2 utilisation allows the typically fossil-origin carbon atoms within fuels to instead be derived from captured CO_2, thus recycling the carbon atoms and avoiding the use of carbon from fossil resources. The CO_2 that is sequestered in the product is released on combustion of the fuel with retention times likely to be less than 1 year[101]. The mitigation potential of CO_2 derived fuels therefore arises due to avoidance of fossil production routes, with CO_2 only mitigated if the CCU production route has lower levels of emissions in comparison.

There may be additional benefits, for example if synthetic fuels burn cleaner or if the CCU fuels are considered a replacement for an alternative type of fuel (e.g. DME substituting diesel). The option for more distributed production is also a potential benefit. However, most end-uses of fuels already have an established low-carbon option that could dominate future markets. Compared to these competitive routes, synthetic fuels can offer the advantage of re-using existing distribution infrastructure and assets, although their production involves additional energy losses compared to direct electricity or hydrogen use.

This chapter discusses the use of CO_2 as a feedstock for the production of middle distillate hydrocarbons (diesel, gasoline, jet fuel), synthetic methane, dimethyl ether, ethanol, and methanol.

6.1.1 Middle Distillate Hydrocarbons (F-T Fuels)

In 2018 the global demand for transport fuels (diesel, gasoline, jet fuel) was estimated at 2900 Mt per year[102]. These fuels are conventionally all produced from the refining of crude oil and can be grouped together under the umbrella term of 'middle distillate hydrocarbons'.

Middle distillate hydrocarbons are conventionally produced from the refining of crude oil. This involves locating the oil fields, drilling wells, extracting and refining/distilling the resulting crude into the gasoline, diesel fuel and jet-fuel products. Additives then may need to be added before the product is ready to be sent to the marketplace. The composition of crude oil differs depending on the region of the world where it was extracted and this partially determines the refining required to create the commodities. Also, practices in extraction and refining of the crude differ in different regions (such as flaring of the gases which are released during crude oil extraction). Due to these reasons, the cradle-to-gate emissions (or well-to-tank in fuel terms) for these products do vary across the world. In the UK, overall life cycle emissions are deemed to be split as 20% from production (well-to-tank) and 80% from end-use (tank-to-wheel)[103].

CO_2 can be combined with hydrogen to produce a synthetic crude oil. This occurs via conversion of CO_2 to CO followed by Fisher-Tropsch synthesis. The synthetic crude is then refined into the final fuel using the conventional refining process. The Fischer-Tropsch process is already commercialized but the conversion of CO_2 to CO is less well developed. This can either occur using the reverse water gas shift reaction, which is more widely understood, or via co-electrolysis of steam and CO_2, which offers the promise of high efficiency.

Alternatively, CO_2 derived methanol can be upgraded to gasoline via the established methanol-to-gasoline process. As discussed in section 4.1.1, methanol can be produced via the hydrogenation of CO_2.

[101] IEA 2019, Putting CO_2 To Use
[102] IEA, World demand by product groups, 2017-2018 [online chart, accessed Oct 2020] [LINK]
[103] According to figures from the UK government GHG conversion factors for company reporting

The technology to convert methanol to gasoline was developed by Mobil in the 1970s and its use is already established for fossil-based methanol.

The synthetic crude route has been demonstrated at small scale with plans for industrial-scale deployment in Norway starting from 2023. The production of synthetic crude from feedstocks of CO_2 and water via a co-electrolysis route is being developed by Sunfire. The company built a pilot plant in Dresden that produced its first batches of synthetic diesel in 2015[91] and has since been involved with the development of plans for industrial-scale deployment in Norway (Norsk e-fuel). The first plant is expected to go into operation at capacity of 10 million litres in 2023, with a 10-fold increase in capacity by 2026[107].

CO_2 utilisation for fuels can have land and water advantages over biofuel alternatives. Overall water use for synthetic middle distillates is approximately 1.4 L per litre of fuel[104]. This is of a similar order to water use for conventional fossil fuels (3-6 L per litre of gasoline) but is around 1000 times less than biofuel pathways, with ethanol production from sugar beet requiring 1400 L per litre of fuel[104]. Land-use is also an important consideration if comparing synthetic fuels to biofuels, with synthetic fuels needing land for renewables and biofuels needing land from crop cultivation. It is reported that the use of one hectare of land would produce 580-1070 GJ or 470-1040 GJ of fuel annually if used for powering CCU via utility-scale solar PV or onshore wind respectively[104]. The majority of this land (67% and 95% respectively) would still be available for agricultural production. In comparison, a best-case biofuel route using algae oil produces 156-402 GJ annually per hectare[104].

[104] Umwelt Bundesamt, 2016. Power to liquids: Potentials and Perspectives for the Future Supply of Renewable Aviation Fuel [LINK]

Assessment: Middle Distillates (F-T Fuels)

Sub-criteria score

Mitigation Potential (Score: 5)

Emissions Avoided[a]: 5

A study based on the Sunfire demonstration plant reported that emissions are 11 or 28 g CO_2-eq / MJ fuel if the electricity is German-based wind or solar PV respectively. This compares to 87.5 g CO_2-eq / MJ for the fossil route.

70-90% reduction

Cradle-to-grave GWP reduction cf. counterfactual

Total Addressable Market[b]: 4

The CCU technology produces synthetic crude that which then undergoes hydrocracking/refining to produce the final fuels, which could be diesel, gasoline or jet fuel. The total existing market for these fuels is estimated at 3 Gt.

3 Gt / yr

Market Uptake Potential (Score: 2)

Commercial Development: 3

Market interest exists. There are plans for an industrial-scale deployment in Norway (Norsk e-fuel). Sunfire have been successful in gaining venture capital from investment rounds. Other companies have demonstrated the technology.

Industrial-Scale Deployment Planned | Venture Capital

Policy & Regulatory Factors: 2

CCU relies on fuel mandates to increase market demand, requiring CCU fuels to be recognized in these mandates. The lengthy and expensive testing and approval process for new fuels can act as a barrier to new entries, especially in aviation.

Total Addressable Market 4

Low Carbon Competition: 1

Established low-carbon options exist for road transport, but CCU fuels are projected to penetrate the heavy-duty trucks market. The main use for CCU fuels is expected to be as an aviation fuel as this market has limited alternatives.

Cost & Value Proposition: 2

CCU is more expensive than the conventional route.

Scalability (Score: 3)

Policy & Regulatory Factors 2

Technical Deployment Factors: 3

Requires a new plant with engineering novelty. Existing distribution infrastructure can be used. Hydrogen production requires access to renewable electricity and fresh water, which could restrict deployment in some regions.

Current TRL: 4

Demonstration plant in Germany. Industrial plant planned for 2023.

TRL 8 | Demonstration Plant

Energy Demand: 1

High level estimates suggest that the CCU route is 15 times more energy intensive than the counterfactual route.

Higher Energy Demand

Other Impacts (Score: 3)

Social & Environmental Impacts: 5

Cleaner burning fuels with reduction in NOx, SOx and particulates. Allows continued use of existing refining assets and vehicle stock.

Energy Demand 1

Water & Land Use: 4

Land use is similar to the counterfactual route whereas water use is significantly lower.

(a) Umwelt Bundesamt, 2016. Power to liquids: Potentials and Perspectives for the Future Supply of Renewable Aviation Fuel
(b) IEA Oil Information 2020

Assessment Outcomes

- **CO_2 Mitigation Potential:** Mitigation potential is highly dependent upon the electricity source used for green hydrogen production, with low-carbon electricity being a requirement for CCU routes to achieve lower life-cycle emissions than fossil routes. A study based on data from the Sunfire demonstration plant reported cradle-to-grave CCU emissions of 11 or 28 g CO_2-eq per MJ fuel if the electricity is German-based wind or solar photovoltaics respectively[105]. This contrasts with estimates of 87.5 g CO_2-eq per MJ for fossil-based jet-fuel[106] giving a cradle-to-grave emission reduction of 87% or 68% respectively. Counterfactual emissions are however dependent upon the source of the crude oil and the practices used when drilling and refining (such as flaring etc) and therefore emission benefits will vary with region. There is a large existing market for middle distillate hydrocarbons as fuels, providing the theoretical platform for 10 Gt of abatement annually if all such fuels were displaced by the CCU route. This however is highly unlikely given the established low-carbon routes for road transport and the existence of bio-based alternatives for aviation. A more realistic mitigation potential is estimated at 0.5 Gt CO_2 per year, assuming a market demand of 150 Mt of CCU fuel.
- **Market Uptake Potential:** The CCU route shows early market potential as evidenced by the recent progress made by Sunfire. The company, as part of a consortium Norsk e-fuel, have commissioned an industrial-scale commercial plant in Norway to be operational by 2023 with increased capacity (100 ML / y) by 2026[107]. Sunfire have also been successful in gaining venture capital from investment rounds and has received equity investment from Neste, a provider of sustainable aviation fuels[108]. The CCU route is not cost-competitive with the fossil hydrocarbon route, however its status as a sustainable fuel gives it added value in some regions due to the existence of market drivers such as sustainable fuel mandates. It is claimed that the CCU route could become cost competitive with advanced bio-fuels with the advantage of not being constrained by biomass availability[109]. For road transport there are already established low-carbon options (EVs and FCEVs), but CCU fuels are projected to penetrate the heavy-duty trucks market. The main use for CCU fuels is expected to be as an aviation fuel as this market has limited alternatives. Existing regulations allow F-T synthetic fuels to be blended to 50% with conventional fuels.
- **Technical scalability:** Although the technology is well-developed (TRL 8), its deployment requires a new facility with potentially novel engineering challenges. The requirements for large amounts of low-cost, renewable electricity is expected to act as a constraint, restricting the locations in which the technology can be deployed. The ability to use existing distribution infrastructure may facilitate near-term deployment when compared to other low-carbon options, such as hydrogen.
- **Other Impacts:** High level estimates suggest that the CCU route is 15 times more energy intensive than the counterfactual route. Large scale deployment would therefore have considerable energy system implications. Compared to fossil-based routes, fuels produced from the CCU route are reportedly cleaner burning with lower NOx, SOx and particulate emissions. It is also reported that the route has lower water consumption. There will be social and environmental benefits from the reduced consumption of fossil resources. In addition, from a societal perspective, the use of synthetic fuels allows for the continued use of existing refining, distribution, and end-use assets.

[105] Umwelt Bundesamt, 2016. Power to liquids: Potentials and Perspectives for the Future Supply of Renewable Aviation Fuel [LINK]
[106] Based on data from: BEIS 2020, Greenhouse gas reporting: conversion factors 2020 [LINK]
[107] 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]
[108] Neste 2020, Press Release: Neste invests in Sunfire, leading technology developer of high-temperature electrolysis and Power-to-X solutions [LINK]
[109] GreenAir 2020, Article: Europe's first power-to-liquid demo plant in Norway plans renewable aviation fuel production in 2023 [LINK]

6.1.2 Synthetic Methane

Methane is the main component of natural gas. Conventionally methane is produced through drilling, extraction and purification of natural gas with a total annual demand of 3 Gt (oil equivalent). Its end-uses as a fuel are mainly in power generation and heating.

Methane can be produced synthetically from CO_2 **and hydrogen.** There are both chemical and biological pathways to convert CO_2 and hydrogen to methane. Chemical pathways include the catalytic hydrogenation of CO_2 and the electrolytic reduction of CO_2. Biological pathways include the fermentation of CO_2-derived syngas by *Clostridium* bacteria. The chemical pathway considered here for life-cycle assessment is a variation of the Sabatier reaction called the TREMP process by Haldor Topsoe, but other developers include ETOGAS.

Multiple pilot-scale projects exist for Power-to-Methane, mostly deployed in Germany. Small scale methanation projects have existing in Europe since the early 2010s[110] for both chemical and biological conversion routes. Many of these have piloted feeding the synthetic methane into existing gas networks, for example the STORE&GO project in Germany[111]. As of 2019, there were 4 European projects with a capacity greater than 5 $MW_{elec.}$ that were either planned or in operation[110].

Hydrogen requirements mean land, water and energy demands are greater than natural gas extraction. Since conventional methane is produced from natural gas which has a relatively low land/water use, it is likely that the CCU route will have higher land/water use due to the high hydrogen requirement. High level estimates suggest that the CCU route would require significantly greater energy demand than the counterfactual process, with high level estimates suggesting requirements of 25 MWh/tonne and 1.25 MWh/tonne respectively for CCU and counterfactual routes.

[110] Theme at al. 2019, Power-to-Gas: Electrolysis and methanation status review [LINK]
[111] https://www.storeandgo.info/demonstration-sites/germany/

Assessment: Synthetic Methane

Sub-criteria score

Mitigation Potential (Score: 5)

Emissions Avoided[a,b]: 5
It is estimated that the CCU route has 22% of the emissions of the conventional route, with a reduction of 2.2t CO_2-eq per tonne of methane.

78% reduction
Cradle-to-grave GWP reduction cf. counterfactual

Total Addressable Market[c]: 4
Current global natural gas demand is approximately 2 Gt (3 Gtoe). Synthetic natural gas has multiple potential future markets including the existing market, as a transport fuel and as a chemical feedstock.

2 Gt / y

Market Uptake Potential (Score: 2)

Commercial Development: 3
Market interest exists for the use of low-carbon methane (currently biomethane) for transport and heating applications. Audi uses an offset system for selling its (demonstration plant) e-gas to customers via the natural gas network.

Total Addressable Market 4

Low Carbon Competition: 1
There are alternative grid-balancing options including batteries and power-to-hydrogen. As an energy carrier, there is competition from other low-carbon options (such as hydrogen and electrification) but CCU could benefit from allowing continued use of existing assets.

Policy & Regulatory Factors: 1
The route is not cost competitive so would require significant policy support to drive market demand. No regulatory barriers preventing product use are identified.

Cost & Value Proposition[d]: 3
CCU is 4-5 times more expensive than the fossil route, with costs highly dependent upon electricity price. Its value lies in use as a low-carbon energy vector and the grid-balancing potential of power-to-gas.

Scalability (Score: 2)

Policy & Regulatory Factors 1

Current TRL: 4
Multiple pilot-scale projects, with 4 European projects (planned/operational) at greater than 5 MW capacity.

TRL8 | > 5 MW Pilot Projects (4)

Technical Deployment Factors: 3
Requires a new plant but can use existing distribution infrastructure. Hydrogen production requires access to renewable electricity and fresh water, which could restrict deployment in some regions.

Energy Demand: 1
Green hydrogen production requires large amounts of low cost, renewable electricity. Total energy is 20 times conventional.

High Energy Demand

Other Impacts (Score: 2)

Social & Environmental Impacts: 4
CCU provides an opportunity to integrate intermittent renewables into existing energy infrastructure, with no alterations to end-user appliances. Benefits from displacing fossil feedstocks.

Energy Demand 1

Water & Land Use: 1
Increased land and water use is expected due to the requirements for hydrogen production and associated renewables deployment.

(a) Bongartz et al. 2018, Comparison of light-duty transportation fuels produced from renewable hydrogen and green carbon dioxide
(b) BEIS 2020, Greenhouse gas reporting: conversion factors 2020
(c) Based on IEA Natural Gas Information Overview (value for 2019 production convert to Gt)
(d) ECOFYS 2017, Assessing the potential of CO_2 utilisation in the UK

Assessment Outcomes

- **CO_2 Mitigation Potential:** Cradle-to-grave estimates based on reported emissions suggests that the CCU route has 22% of the emissions of the conventional route, with a reduction of 2.2 t CO_2-eq per tonne of methane[112,113]. Emission reductions are achieved both through avoidance of upstream emissions associated with the fossil route and through the re-use of captured CO_2. The extent to which CO_2 is mitigated will depend up the emission intensity of the electricity used for CCU and assumptions around the counterfactual emissions. If the entirety of the existing market for methane were to convert to the CCU route then the total CO_2 mitigation potential would be or the order of 4 Gt CO_2-eq per year.
- **Market Uptake Potential:** Existing interest in biomethane for transport and heating applications suggest that there is potential for low-carbon methane in these markets. However the CCU route is expected to be significantly (4-5 times) more expensive than the fossil route, so considerable policy or regulatory support is likely to be necessary in order to drive market demand. Furthermore, there are several established low-carbon alternatives for methane in heating and power applications - such as electrification, fuel switching to hydrogen, and CCS – which are expected to limit market uptake. CCU methane may have added value for its grid-balancing potential (PtG), however there are also alternatives for this such as battery storage and hydrogen production.
- **Technical scalability:** The technology is reaching the later stages of development with multiple pilot and demonstration projects in existence, particularly in Europe. The requirements for large amounts of low-cost, renewable electricity is expected to act as a constraint, restricting the locations in which the technology can be deployed. The ability to use existing distribution infrastructure for the SNG may facilitate near-term deployment when compared to other low-carbon options.
- **Other Impacts:** The route provides an opportunity to integrate intermittent renewables into existing energy infrastructure, with no alterations to end-user appliances. There will be social and environmental benefits from the reduced consumption of fossil resources. Due to its requirement for green hydrogen, the CCU route will likely have higher land and water use compared to the conventional route which has relatively low use of these resources.

6.1.3 Dimethyl Ether (DME)

DME is produced from catalytic dehydration of methanol, with methanol produced from syngas (CO + H2) either in situ or in a separate initial step depending on the technology used. This syngas is typically derived from natural gas or coal, but it can also come from biomass gasification. A CO_2 utilisation route would use methanol derived from CO_2, rather than syngas. This could occur separately, as described in section 4.1.1, or within the same reaction vessel using a $Cu.ZnO.Al_2O_3$ catalyst.

Dimethyl Ether (DME) is emerging as a potential alternative to diesel for the heavy-duty trucks market. DME is a non-toxic and environmentally benign chemical that has properties similar to propane. In most regions it has end-uses in personal care, household and paint products, mostly as a propellant in aerosols, however in China it is widely used as a fuel, with blends of up to 20wt% permitted in LPG. In the US, DME has been approved as a transport fuel, with DME from biomass gasification given renewable fuel status. Here DME is seen as a potential alternative to diesel. Oberon Fuels is producing DME for Volvo/Mack and Ford Trucks. Use of DME as a standalone fuel requires engine modifications. DME is also reported as a potential marine fuel.

LCAs have shown environmental benefits of DME produced from CO_2. Conventional DME has environmental benefits over diesel (cleaner burning, non-toxic/beign/degrades) however additional benefits

---

[112] According to “Bongartz et al. 2018, Comparison of light-duty transportation fuels produced from renewable hydrogen and green carbon dioxide” cradle-to-grave emissions of CO_2-derived methane are 14.1 g CO_2e/MJ

[113]According to “BEIS 2020, Greenhouse gas reporting: conversion factors 2020 [LINK]” emissions of fossil-derived methane are 2,872 kg CO_2e/t and the net calorific value of natural gas is 44.76 GJ/tonne.

are seen for DME produced using CO_2 as a feedstock. These stem from the same benefits achieved with producing methanol from CO_2 as discussed in section 4.1.1.

Assessment: Dimethyl Ether (DME)

Sub-criteria score

Mitigation Potential (Score: 4)

Emissions Avoided[(a)]: (5)
Cradle-to-grave greenhouse gas emissions of CO_2-derived DME are approximately 14% of those from DME produced conventionally from natural gas. This equates to reductions of 70 g CO_2-eq per MJ of DME.

86% reduction
Cradle-to-Grave GWP reduction cf. counterfactual

Total Addressable Market[(b)]: (3)
DME currently has uses in household products, aerosol propellants, and paint. A fuel market for DME as a diesel alternative is emerging. Converting the global heavy-duty trucks market to DME would give a market in the region of 500 Mt.

500 Mt / yr
Estimated future DME market if used as an alternative to diesel in trucks

Market Uptake Potential (Score: 2)

Commercial Development: (1)
No commercial development known for use of captured CO_2 specifically. Oberon Fuels in the US uses either stranded natural gas or biogas (both mixtures of methane with up to a maximum of 50% CO_2) in a dry reforming process, marketed as renewable DME.

Policy & Regulatory Factors: (2)
DME is approved as a transport fuel in some regions. Production of DME by a new CCU route would need to undergo the fuels testing and approvals process.

Total Addressable Market (3)

Low Carbon Competition: (1)
Established alternatives exist. Although DME can allow continued use of existing assets via engine retrofit.

Cost & Value Proposition: (3)
Not expected to be cost competitive with conventional DME route but may realise value for 'sustainability'. Use of DME instead of diesel could reduce the need for expensive diesel particulate filters on truck engines.

Scalability (Score: 2)

Policy & Regulatory Factors (2)

Technical Deployment Factors: (3)
Requires CCU methanol production – new plants, access to renewable electricity, water requirements. CCU methanol can be used in the existing methanol-to-DME process. Engine retrofits are needed for DME use as a diesel alternative.

Current TRL: (2)
The methanol-to-DME process is established with fossil-based methanol. CCU methanol is at TRL8.

Uses Known Processes

Energy Demand: (1)
CCU requires significant energy demand for hydrogen production. Energy consumption is much higher than the conventional route.

High Energy Demand

Other Impacts (Score: 3)

Social & Environmental Impacts: (5)
Benefits from displacing fossil feedstocks but impacts from renewables deployment. Compared to diesel, DME combustion emissions are lower in CO, SOx and NOx.

Energy Demand (1)

Water & Land Use: (3)
Limited information available. Estimates of lower water consumption but increased land-use.

(a) Matzen M and Demirel Y (2016). Methanol and dimethyl ether from renewable hydrogen and carbon dioxide: Alternative fuels production and life-cycle assessment

(b) Based on IEA ETP value for heavy-duty truck diesel market

Assessment Outcomes

- **CO_2 Mitigation Potential:** Cradle-to-grave greenhouse gas emissions of CO_2-derived DME are approximately 14% of those from DME produced conventionally from natural gas[114]. This corresponds to reductions of 70 g CO_2-eq per MJ of DME. The total mitigation potential is limited by the addressable market size for DME.
- **Market Uptake Potential:** The route has not been developed commercially, however developments for the Oberon Fuels process (non-CCU) illustrate a market interest in renewable DME as a fuel. Barriers expected to limit market uptake are CCU costs, existence of competitive options, and regulations. The CCU route is expected to be more expensive than conventional DME production, with a CCU methanol feedstock being twice the cost of conventional methanol feedstock. Furthermore, there are established competitive options for the heavy-duty trucks market, such as hydrogen FCEVs, that may split market interest. Although DME is approved as a transport fuel in the US, regulatory approval in other regions would be needed to allow wider market uptake.
- **Technical scalability:** The ability to deploy at-scale will depend upon the ability to process CCU methanol at comparable scales, as this is a feedstock for the assessed route. As discussed previously in Section 4.1.1, CCU methanol production requires construction of a new plant, access to renewable electricity, and it has water requirements. This CCU methanol can then be used in the existing methanol-to-DME process. An expansion of DME end-uses into the broader heavy-duty-trucks market would require new engine designs and engine retrofits on existing vehicle stock, which would constrain the rate of deployment.
- **Other Impacts:** CCU route requires significant energy demand for hydrogen production, with associated energy system implications. Additional impacts come from reduced fossil consumption and increased renewables deployment. Estimates suggest the CCU route may have lower water consumption but increased land-use compared to conventional DME. If DME is used as an alternative to diesel then there are lower combustion emissions (CO, SOx and NOx) which avoid the need for expensive diesel particulate filters on truck engines. These benefits would, however, still be achieved using conventional DME as the alternative, so are only additional over direct fossil fuel use.

6.1.4 Ethanol

The dominant end use of ethanol is as a fuel or fuel additive, with other uses being as an industrial solvent, for use in alcoholic beverages and personal care products such as hand sanitizer and cosmetics. The demand for ethanol as a bio-fuel is growing, however regulations limit ethanol blending in gasoline several percent per volume. Ethanol as a transport fuel will face competition from other alternative fuels such as electric and hydrogen vehicles.

The conventional route considered is the production of bio-ethanol from crops such as sugar beet, sugar cane and maize. Until the 1980's, ethanol production required petrochemical-derived ethylene (itself an energy intensive process) which was hydrated to ethanol using phosphoric acid as the catalyst. However, most ethanol is now 'bio-ethanol' produced by yeast fermentation of plant sugars. This route uses large quantities of water (40-100 L/MJ dependent on the crop) and large areas of land (production of 80-150 GJ/Ha/yr dependent on the crop) for crop growth[115]. The route is also subject to volatile crop prices, limitations in availability, and competition with food for crops.

Routes to producing ethanol from CO_2 **include electrochemical reduction and biological fermentation:**

- **Electrochemical reduction:** The routes reported in the literature are at lab-scale with low levels of technology development, with further research needed on catalyst development. However it is

[114] Matzen M and Demirel Y (2016). Methanol and dimethyl ether from renewable hydrogen and carbon dioxide: Alternative fuels production and life-cycle assessment
[115] Umwelt Bundesamt (2016). Power to liquids: Potentials and Perspectives for the Future Supply of Renewable Aviation Fuel.

understood that Air Company uses an electrochemical reduction process to produce ethanol which is then sold as Vodka. Details of the precise process are not made public. The company claims that the process is net-negative, removing 1.5 t CO_2 / t CO_2 utilised as assessed through LCA[116], details behind this assessment are unavailable and the boundaries are unknown.

- **Biological fermentation:** Acetogenic bacteria can ferment gaseous mixtures of CO_2/H_2 to C_2 compounds such as acetate and ethanol under anaerobic conditions however the route faces challenges with substrates. The bioogical conversion of syngas (CO and H2) to ethanol is much more advanced and is being developed/commercialised by Lanzatech. The company are reportedly developing a new process that can use CO_2 as 50% of the carbon source with a pilot facility planned. In the past, Joule completed pilot testing for a light assisted CO_2 and H2O bioconversion, but the project was discontinued.

116 https://aircompany.com/pages/science [accessed Jan 2021]

Assessment: Ethanol

Sub-criteria score

Mitigation Potential (Score: 4)

Emissions Avoided[(a)]: 5

Air Co. claims that its process is net-negative, removing 1.5 t CO_2 / t CO_2 utilised as assessed through LCA. However, the details behind this assessment are unavailable and the boundaries are unknown.

Total Addressable Market[(b)]: 3

The dominant end use of ethanol is as a fuel or fuel additive, with other uses being as an industrial solvent, for use in alcoholic beverages and personal care products such as hand sanitizer and cosmetics. The demand for ethanol as a sustainable fuel is growing.

100 Mt / y

Market Uptake Potential (Score: --)

Commercial Development:

Several companies have been involved with developing different CO_2 to ethanol technologies. Air Company have produced and sold CCU products at pilot-scale (Vodka and personal care products). Lanzatech is pursuing ethanol from flue-gas technologies. Market interest for CCU ethanol as a fuel is unclear, but demand exists for bio-ethanol.

Total Addressable Market 3

Low Carbon Competition: 1

Established competitive options exist for road transport fuels - EVs and hydrogen FCEVs.

Policy & Regulatory Factors: 3

CCU relies on fuel mandates to increase market demand, requiring CCU fuels to be recognized in these mandates. Regulations limit blending percentages.

Cost & Value Proposition:

Costs for the electrochemical CCU route will depend upon electricity and CO_2 prices. The Joule process targeted a price of USD 0.32 / L which was competitive at the time. Counterfactual costs are dominated by crop prices which are variable.

Scalability (Score: --)

Policy & Regulatory Factors 3

Technical Deployment Factors:

Limited publicly available information on the technologies. The electrochemical route is expected to require large amounts of renewable electricity and water.

Current TRL:

Air Company have a small-scale facility and a larger demonstration plant being built. Lanzatech plan to build a pilot plant that will use 50% CO_2 as the carbon source.

Small-Scale Pilot

Energy Demand: 2

High level estimate that the CCU energy demand is slightly (10-20%) greater than bio-ethanol.

Small Increase

Other Impacts (Score: 4)

Social & Environmental Impacts: 5

Unlike bio-ethanol, CCU ethanol is not associated with competition for food crops. CCU route does not require fossil-fertilizer and has benefits from lower land-use.

Energy Demand 2

Water & Land Use[(c)]: 5

CCU fuels use approximately 5 times less land than bio-fuels and 100 times less water.

(a) Air Co (2020). Available at: https://aircompany.com/pages/science
(b) Renewable Fuels Association 2019
(c) Umwelt Bundesamt (2016). Power to liquids: Potentials and Perspectives for the Future Supply of Renewable Aviation Fuel.

Some sub-criteria have not been scored due to a lack of information relevant to the applied scoring system.

Assessment Outcomes

- **CO_2 Mitigation Potential:** No LCAs were identified for the routes and additional information on the processes was limited. Air Co. claims that its product is carbon negative.
- **Market Uptake Potential:** Several companies have been involved with developing different CO_2 to ethanol technologies. Air Company have produced and sold CCU products at pilot-scale (Vodka and personal care products). Lanzatech is pursuing ethanol from flue-gas technologies. Bio-ethanol blending relies on fuel mandates to increase market demand, requiring CCU ethanol to be recognized in these mandates. The competitiveness of CCU ethanol will be dependent on factors associated with bio-ethanol production such as crop prices and availability.
- **Technical scalability:** There is limited information on the CCU routes in development. The routes are entering the demonstration stage with pilot plants planned or under construction. It can be assumed that the electrochemical route will require large amounts of renewable electricity and water which could restrict the locations of deployment. High level estimates indicate that the CCU energy demand is 16% greater than bio-ethanol.
- **Other Impacts:** Unlike bio-ethanol, CCU ethanol is not associated with competition for food crops. The CCU route also does not require fossil-fertilizer and has benefits from lower land-use. It is reported that the CCU route uses approximately 5 times less land than bio-fuels and 100 times less water.

6.1.5 Methanol as a Fuel

Methanol can be blended with gasoline or used directly as a fuel. A significant existing end-use of methanol is in the fuels sector, with 14% of methanol used in gasoline blending and fuel combustion[117]. Trials have shown methanol blends of 15% (M15) to be suitable for standard combustion engines and M15 blends are already used extensively in China[118]. Fuel quality standards however restrict the level of methanol blending in motor gasoline, limiting blending to 3% by volume in Europe and 5% in the United States[119]. The use of methanol as a fuel is popular in China, which has vast coal reserves but limited oil and gas reserves. The region uses methanol in various blends ranging from 5% to 100% methanol, accounting for 7-8% of China's transport fuel use[119]. Specialist car, bus and truck engines that can run on 100% methanol have been developed and deployed in China, with M100 cars trialled in Iceland using methanol from CRI[118]. Methanol is also regarded as a promising alternative for marine fuels[119].

CO_2 utilisation for the production of methanol was discussed in more detail earlier in the chemicals chapter of this report (Chapter 4). However, due to the existing use and future potential of methanol as a fuel the commodity is also included here with modifications to the assessment to reflect methanol used as a fuel. The main changes were that as a fuel (compared to as a chemical) methanol: has a larger addressable market size (acting to increase mitigation potential and market interest); has greater low-carbon competition (acting to lower market interest) but also has more regulatory support (acting to encourage uptake).

[117] Data is from the MMSA shared via the Methanol Institute, available here: https://www.methanol.org/methanol-price-supply-demand/
[118] Methanol Institute 2019, Overview of Global Methanol Fuel Blending [presentation] [LINK]
[119] IEA AMF webpage on Fuel Information: Methanol [accessed Jan 2021] [LINK] (5% blend in the US using the "Octamix" waiver requires a minimum of 2.5% of co-solvents)

Assessment: Methanol as a Fuel

Sub-criteria score

Mitigation Potential (Score: 4)

Emissions Avoided[a]: 4

CCU methanol has a lower global warming impact than fossil methanol if low-carbon electricity is used for water electrolysis. Mitigations of the order of 1.5 t CO_2 avoided per tonne of methanol are reported.

1.5 t CO_2/t — Cradle-to-Gate emission reduction per tonne of methanol

Total Addressable Market[b,c]: 3

Low-levels of gasoline blending (3%) give a potential market size of 34 Mt whereas higher-levels (15%) give a market size of 170 Mt. In the longer-term, CCU methanol (or its derivatives) could be used directly as a fuel (100%) with accessible markets being the marine fuels sector (200 Mtoe) and heavy-duty trucks (600 Mtoe).

Market Uptake Potential (Score: 3)

Commercial Development: 4

A CRI demonstration facility (4 kt/y) markets its CCU methanol commercially in Europe. The company has a contract to deliver a large-scale plant in China and has received investments from private companies including a Chinese car manufacturer.

Total Addressable Market 3

Low Carbon Competition: 2

Several established competitive options including bio-fuels, EVs and FCEVs. These have limitations in biofuel availability and requirement of new vehicle stock.

Policy & Regulatory Factors: 3

The high commodity price means the route is reliant on fuel mandates to increase market demand. This type of mandate already exists in some regions. Specifications limiting fuel blending and what types of fuels constitute as 'sustainable' act as a barrier.

Cost & Value Proposition: 3

The CCU route is not expected to reach cost-parity with fossil methanol. Its value proposition is as a sustainable fuel.

Scalability (Score: 3)

Policy & Regulatory Factors 3

Technical Deployment Factors: 3

A new plant is required but technology is modular and no significant engineering challenges are envisaged. The route requires large amounts of renewable electricity for hydrogen production, but this can be intermittent.

Current TRL: 4

CRI have a small-scale commercial plant in Iceland and pilot projects for specific applications.

TRL 8 | 4 kt/y Demonstration Plant (2015)

Energy Demand: 1

Green hydrogen production requires large amounts of low cost, renewable electricity.

High Energy Demand

Other Impacts (Score: 2)

Social & Environmental Impacts: 3

Potential for immediate drop-in to existing vehicle-stock via blending. Methanol has low toxicity compared to ammonia (marine fuels). Cleaner burning than other fuels.

Energy Demand 1

Water & Land Use: 1

Increased land and water use due to need for hydrogen production and renewables deployment.

(a) Bazzanella et Ausfelder 2017, Low carbon energy and feedstock for the European chemical industry. Technical study.
(b) IEA Oil Information 2020 - gives 2018 motor gasoline demand as 1131 Mt
(c) IEA Energy Technology Perspectives 2020 – data on marine fuels and heavy-duty trucks demands

6.2 Strengths, Weaknesses & Discussion (Fuels)

The primary criteria results for CCU fuels are shown in Figure 10. It was not possible to provide high-level scores for CCU ethanol due to data gaps in the assessment. The routes assessed had adequate to low performance in most categories, but good performance under mitigation potential. This implies that in general the use of CO_2 as a feedstock for fuels has the potential to:

- **Achieve good levels of emission mitigation:** These routes can result in significantly less GHG emissions per tonne and have large addressable markets in most cases. CO_2 sequestration is however temporary (<1 years) with emissions mitigation due to the re-use of CO_2 and avoidance of fossil feedstocks.
- **Receive limited, niche market interest:** There is some interest in developing CCU routes, however there is currently a lack of market drivers for uptake. Competitive options limit the likely penetrable market share to specific / niche end-uses.
- **Scale production with conditions:** Technologies could be deployed in appropriate locations (access to renewables, water, approved by regulations) at scale, but some routes need further RD&D. Energy demand is a barrier to achieving global scale.
- **Have adverse impacts:** On average, deployment of technologies could adversely impact energy systems and use of resources (land, water).

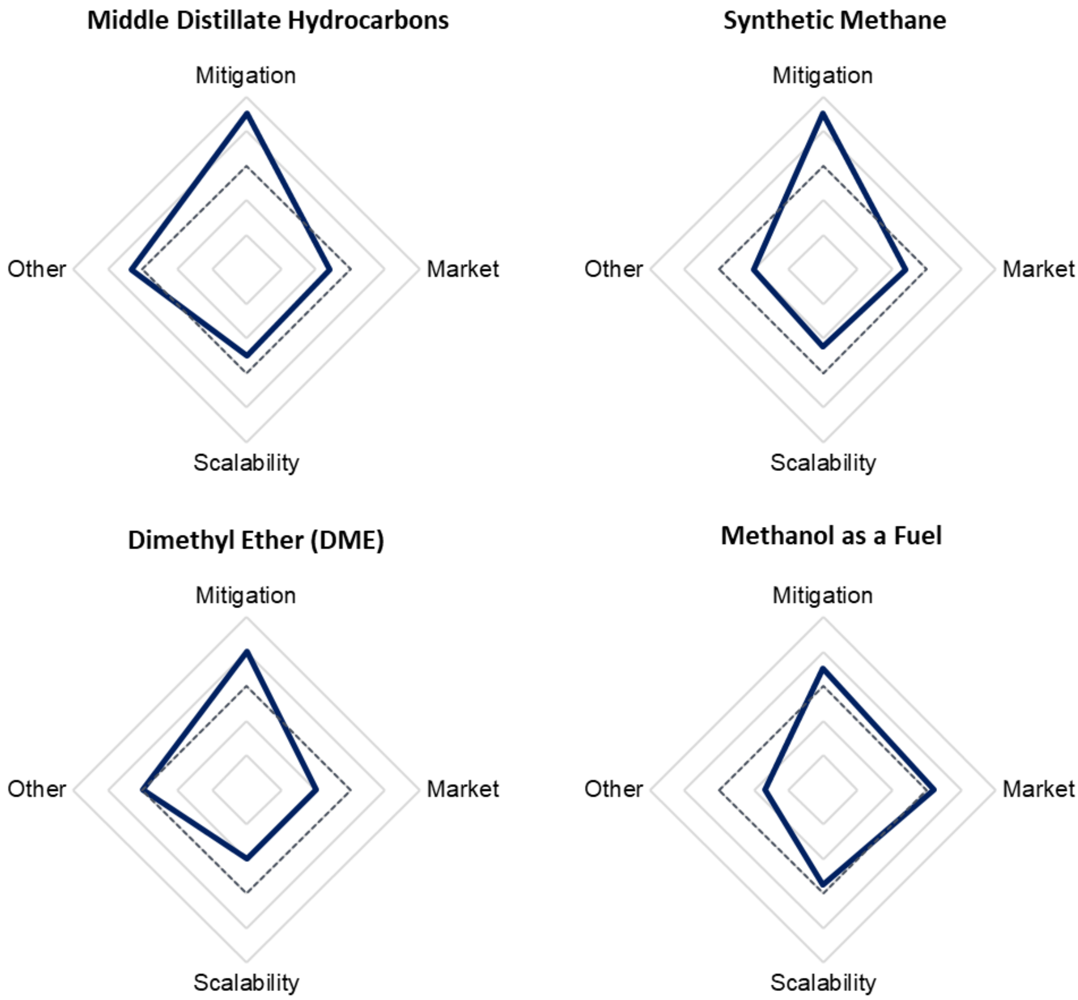


Figure 10: Radar plot of primary criteria scores (1-5) for **fuels,** with higher scores indicating an area of strength. The approach to scoring is detailed in Section 2.2 of this report and follows a comparative approach between all commodities investigated. **Mitigation:** The ability of the CCU route to lead to emissions abatement in the future, if there are no technology or economic barriers. **Market:** The ability of the CCU route to have an established future market in a low-carbon world, if there are no technology barriers. **Scalability:** The ability

of the CCU route to deploy globally or at a large scale, if there is significant market demand. **Other:** The extent to which any additional impacts resulting from CCU deployment are beneficial (high score) or detrimental (low score).

A common strength of CCU fuels is their mitigation potential when to compared to a fossil counterfactual. Providing renewable electricity is used for hydrogen production, the routes offer significant reductions in CO_2 emissions per tonne compared to the equivalent fossil-derived product. This combined with the large existing markets for fuels means that the routes score highly on the 'mitigation potential' criterion, as significant emissions could be avoided if existing fossil routes were replaced with CCU routes. The caveat however is that in many cases there are alternative abatement routes. It was not within the scope of this study to compare CCU fuels to alternative abatement options and this could be an area for future investigation.

Cost premiums and existence of established alternatives are key limitations for 'market uptake potential'. The significant cost premium of the routes is a key barrier to adoption, meaning that ambitious political/regulatory support mechanisms are needed for successful market uptake. Furthermore, existing, well-established low carbon alternatives for fuels and have the potential to take a significant share of the market, limiting the possible penetration of CCU fuels.

There are technical barriers to global deployment of CCU fuels, with weaknesses related to energy demand and regulations/standards. The routes result in increased energy consumption and require large amounts of renewable electricity, this is likely to impact the extent to which routes could be deployed at global scale as renewable capacity may be constrained in some regions. New alternative fuels must gain regulatory approval as well as guarantees from engine manufacturers, often requiring significant testing. This acts as a technical barrier to deployment in new regions.

Regional Considerations

Emissions avoidance and other land/water/energy impacts vary by region. Operations for the extraction and refining of conventional fossil fuels can vary in their emission intensity, the result being that average counterfactual emissions (as well as land, water, and energy demand) vary between regions. Emissions associated with the CCU routes are highly dependent upon the emission intensity of the electricity used, which would vary with the grid-mix if connected to the grid or can even vary with the type of renewable energy used. The overall emissions avoidance of CCU routes is therefore variable between regions.

CCC fuels would be cheaper to produce in regions with low-cost renewable electricity. The costs of CCU fuels are highly dependent on the costs of electricity, with renewable electricity assumed to be required to obtain the true CO_2 mitigation benefits (a key driver for the routes). Therefore, production of these chemicals could be favoured in regions with low-cost and high availability of renewable electricity, such as the Middle East and North America.

Uptake of CCU fuels is more likely in regions with strong climate policies… CCU fuels are much more expensive than their counterfactuals. Their main market driver is their sustainability however the value of this benefit is only likely to be economically realised in a region with strong climate ambition and suitable policies to support lower emission or more sustainable products. Europe is a region with wide-spread existing support for sustainable fuels. The European Union has directives to mandate the use of more sustainable, lower emission fuels and individual member states also set their own blending obligations. This type of policy support allows sustainable fuels to compete for a market segment that is not accessible to conventional fossil fuels, thus giving them an advantage.

…and where counterfactual costs are high. Although the costs of fuels are high, there are regions where costs of counterfactual products may be higher than global averages, perhaps due to a lack of local fossil reserves or a reliance on imports (Europe, China). Alongside appropriate support mechanisms, this could allow CCU fuels to be more competitive.

The current prevalence and acceptance of competitive low-carbon options also varies regionally, with some areas having made greater progress on the deployment of EVs and FCEVs than others and some regions having greater capacity for biofuel production. Due to their like-for-likeness with conventional fuels, CCU fuels could be favourable in areas where there are particular challenges to deployment of alternative options.

RD&D, Evidence Gaps and Uncertainties

Several companies are working on CCU fuels but their LCA data is not available. Published LCA studies, where available, are generally academic papers evaluating multiple scenarios. Emissions reductions are due to avoidance of fossil fuel use but conventional fossil fuel production (well-to-tank) varies with geography, due to crude oil composition and drilling/flaring & refining practices. No LCAs of CCU ethanol processes were identified.

The co-electrolysis of CO_2 and hydrogen has the potential to change the outlook for CCU methane and middle distillate hydrocarbons. Co-electrolysis of water (steam) and CO_2 in a high temperature solid oxide electrolysis cell (as being developed by Sunfire and Siemens), would enable co-production of H2 and CO (syngas). This route has a higher level of H2 production efficiency than low-temperature electrolysis methods such as PEM and also avoid the reverse water gas shift reaction. Syngas is a conventional feedstock for many existing chemical and fuel routes, and methanation from CO is more efficient than from CO_2.

RD&D is ongoing to improve the reaction efficiency for DME production from CO_2. A sorption-enhanced single-step process has been developed that removes H2O as it is produced which improves the reaction efficiency. LCA data is not yet available the process.

7 Regional Influences

The potential success of CCU technologies is influenced by numerous factors, many of which can vary significantly between countries and/or regions. The previous chapters have discussed the strengths and weaknesses of a variety of CCU technologies, and each have highlighted some key factors that might alter the assessment at a region-specific level. In broad terms:

- **Mitigation potential** is influenced by the emission intensity of the existing production and use methods in the region (fuel type, efficiency, recycling, end-of-life), and the emission intensity of the CCU production route in the region. Examples of how CCU production emissions could be variable with region include: differences in the emission intensity of electricity used (grid mix, renewable availability), the type of CO_2 capture method preferred, and production method of other feedstocks.
- **Market uptake potential** can vary by region due to differences in the establishment or perception of competitive options, differences in the cost & value proposition of CCU routes, and differences in the policy or regulatory environment. Market uptake of CCU may be more favourable in regions with lower cost CCU production, regions with greater counterfactual product costs, and regions with stronger policy/regulatory/public support for sustainable products or emission mitigation.
- **Technical scalability** can be influenced by a region's access to resources, such as renewable energy potential, by a region's regulatory or product approval requirements, or by differences in the ease-of-implementation such as work-force expertise or access to captured CO_2.
- **Other impacts** can vary in severity or relevance by region**.** There will be regional variations in availability of land, water, and energy, with the impact of increased use of resources being more significant in areas where access is scarce. There will also be regional variability in the impact or applicability of broader social and environmental factors, such as job retention or avoidance of waste.

This chapter discusses three key regional variations that could impact the success of CCU routes: fossil resources, deployment of renewables, and policy & regulatory support. The significance of these for CCU deployment and uptake is discussed below. The variations are then illustrated for the regions of Asia (Middle East, China, India), Europe, and North America and the extent of CCU development in the regions is highlighted. Figure 14 at the end of the chapter provides a summary. Further discussions on route specific regional factors can be found in each of the category chapters, Chapters 3-6.

The availability of fossil resources impacts the cost of producing conventional fossil-based chemicals, polymers, and fuels. Chemicals, polymers, and fuels are typically derived from fossil-feedstocks. The capital cost of producing these commodities is partially dependent upon the choice of feedstock, and the operational costs are partially dependent upon the cost of the feedstock. Taking olefins as an example, the coal-based production route used in China is five times more expensive than the naptha-based route in terms of capital costs, but during periods where oil prices are high this is offset by the lower cost of coal[120]. Feedstock costs for the production of petrochemicals are consistently lowest in North America and the Middle East, where there are considerable reserves of natural gas and oil[120].

Importers of fossil resources may be concerned about security of supply, whilst regions that rely on fossil exports may need to diversify. The geographical distribution of fossil reserves means that some regions, such as Europe and China, are reliant on fossil imports to meet domestic energy demands whilst others, such as the Middle East, have developed an economic reliance on fossil exports. There is a drive for some importers to become more self-sufficient due to concerns about energy security, as the cost and supply of fossil resources is known to be volatile. Equally the current low oil prices and future uncertainty in demands for fossil fuels are encouraging some exporters to diversify their economies. Figure 11 shows the variation of petroleum production by country.

The cost and availability of renewable electricity is a significant factor for many CCU routes in chemicals and fuels. Many of chemical and fuel CCU routes use hydrogen produced from electrolysis, meaning that costs are highly dependent upon the cost of renewable electricity. The cost of producing

[120] Deloitte 2019, The Future of Petrochemicals [LINK]

electricity from renewables varies by region, with solar PV installations being lowest in the Middle East and North America and more expensive in Europe and China. In order to achieve optimal emission reductions and avoid negatively impacting energy systems, CCU routes would likely be expected to have a dedicated renewable energy supply. Therefore, a region's efforts to encourage and expand renewables capacity could be an influencing factor for the uptake of these CCU routes. In addition, regions where there is limited opportunity for renewables installations may choose to prioritise the use of these renewables for other decarbonisation routes. Figure 12 shows the variation of renewable electricity capacity by country.

The extent and type of political and regulatory support for CCU is expected to vary by region, with some countries already having support mechanisms in place. The existence of policies that may directly or indirectly support CCU varies by region. Regions have differing track-records in supporting objectives to reduce emissions, for example there is variable support for CCS and for carbon pricing mechanisms. Any support structures used to aid the development of CCU are also likely to vary by region, with some areas preferring free-market mechanisms and others preferring state-ownership structures.

Such regional variations may provide local opportunities for CCU. The development, deployment and uptake of CCU routes may be more favourable in: regions with low-cost renewables or extensive availability of renewable energy (fuels, chemicals); regions with high cost or lack of available fossil resources (fuels, chemicals, polymers); or regions with significant low-carbon ambition coupled with political or regulatory mechanisms to incentivise CCU developments and CCU uptake (all routes).

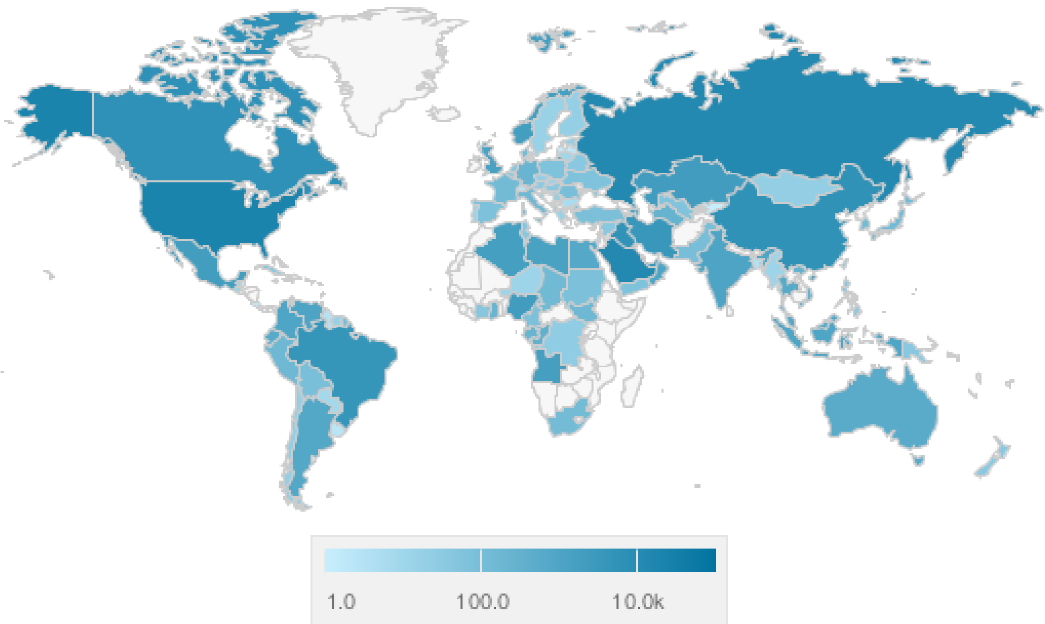


Figure 11: Annual petroleum and other liquids production by country in 2019 (million barrels/day). Sourced from the US Energy Information Administration[121]

[121] US Energy Information Administration [LINK]

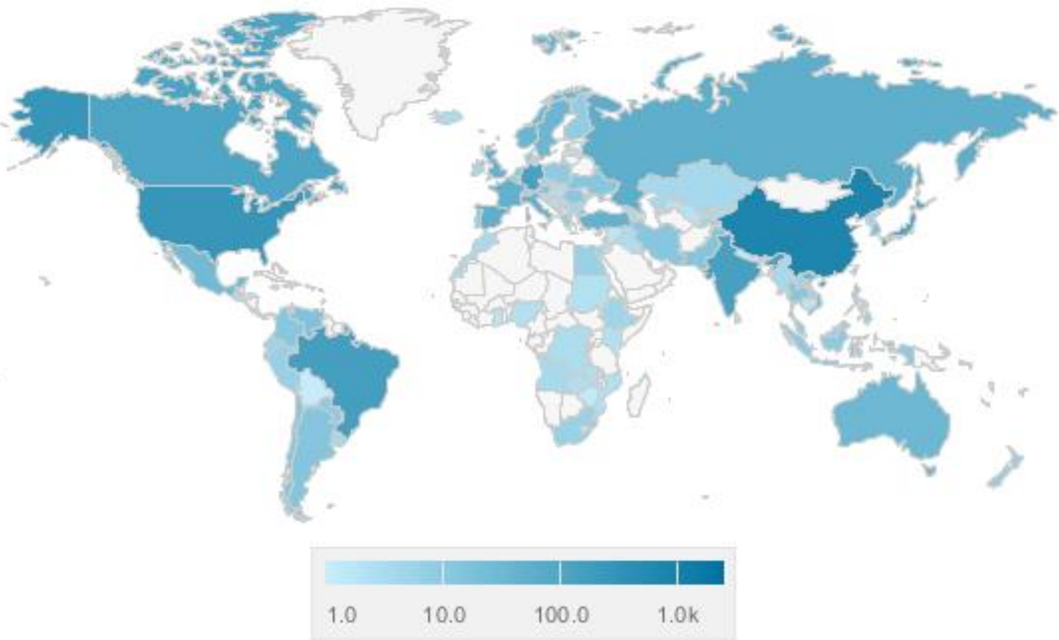


Figure 12: Renewables capacity by country in 2019 (million kW). Sourced from the US Energy Information Administration[121].

7.1 Asia

The Middle East has vast oil reserves with an economic reliance on oil export revenues. The Middle East has vast fossil resources, with Saudi Arabia having 16% of the world's proved oil reserves and being the world's largest exporter of petroleum liquids[122]. The region's economy relies heavily on petroleum exports, with estimates that 60% of revenues for Saudi governments economy being oil-based. In 2016, the majority of crude oil exports were to Asia (69%) whilst refined products went mostly to Asia (45%) and Europe (40%). Saudi Arabia however announced plans to diversify its economic base in its 'Vision 2030' and has a growing petrochemicals sector.

The Asia Pacific area is characterized by an abundance of coal resources with an associated coal-chemicals industry. China and India have an abundance of coal resources, with limited oil and gas reserves. China's oil and natural gas demands exceed domestic production, requiring the imports that in the case of oil mostly come from the Middle East (44%). The region however has vast coal reserves which it aims to monetize through conversion to fuels and petrochemicals. The region uses syngas from coal gasification to produce methanol, which is used widely for fuels and as a chemical feedstock in a developing 'methanol economy'. In 2019, China produced an estimated 108,000 b/d of oil from coal-to-liquids and 500,000 b/d from methanol-to-liquids[123].

Asia has seen significant expansion in the deployment of renewable electricity, with low-cost solar PV in the Middle East. Renewables capacity in the region is growing, with percentage increases of 73%, 60% and 40% for India, China, and the Middle East respectively from 2015 to 2019, corresponding to absolute increases of 54, 282, and 6 GW respectively. Globally, the United Arab Emirates has seen the largest percentage increase in installed renewables generation capacity since 2015, with an increase from 0.1 GW (2015) to 1.9 GW (2019). Over this period, whilst the cost of installing solar PV in China was consistently above the global average, the cost of installing solar PV elsewhere in Asia was typically below average, with particularly low costs in the Middle East[124,125].

[122] EIA 2020, Country Analysis Executive Summary: Saudi Arabia [LINK]
[123] EIA 2020, Country Analysis Executive Summary: China [LINK]
[124] IEA, Average solar PV auction price by region and commissioning date, 2014-2023 [online chart] [LINK]
[125] IEA, Average auction prices for solar PV by region and commissioning date, 2016-2022 [online chart] [LINK]

- **Experience:** There are several large-scale operational CCS projects in the region, including projects in China, Saudi Arabia, and the UAE[126]. CCUS developments in India have been very limited.
- **Carbon pricing:** China is working towards implementing an ETS scheme, with 8 pilot systems underway. Initially this will cover the power sector, with monitoring, reporting and verification (MRV) obligations in other sectors to facilitate gradual expansion[145].
- **Funding:** The region has a history of state involvement and public ownership in power and industry projects. CCS and renewable electricity projects have been enabled through provisions from governments or state-owned companies. For example, in China there is an emerging pipeline of publicly procured carbon capture projects and nearly all electricity is generated by state-owned utilities. Saudi Arabia and the United Arab Emirates have both committed to doubling public investment in clean energy research and development[2] and China has set up several RD&D programmes as part of its 13th Five Year Plan.

There are a limited amount of CCU development projects in Asia. According to analysis of the SCOT database, only 9% of CCU research and development projects are located outside of the EU, US and Canada, of which 2% are located in China[127]. Within this study, Asia was identified as a region with existing use of CO_2 in the production of polycarbonate and a planned production of methanol form CO_2:

- An established production route developed by Asahi Kasei uses CO_2 as feedstock to produce the chemical diphenyl carbonate, which is then used in the production of the polymer polycarbonate.
- The Shunli plant in Henan Province, China is due to commission a project that will retrofit Carbon Recycling International's emission-to-liquids technology to their existing coke oven gas facility. This will allow the plant to supply low-carbon intensity methanol as a by-product to local corporations.

An enabler for CCU in the region is the ability to install **large capacities of low-cost renewables** (solar PV) meaning that hydrogen can be produced cheaply at-scale without impacting existing energy systems. Another enabler is the regions experience with carbon capture projects. If CCU routes can align with the broader ambitions of individual countries, then it is possible that CCU technologies could be **supported or procured by the state** or state-owned entities. Barriers for CCU in the region are the lower climate ambitions and the existence of local, cheap fossil reserves. Potential areas of interest for CCU in the Middle East are in the production of **synthetic fuels using low-cost hydrogen** from solar-powered electrolysis. These fuels could be exported as lower-emission alternatives to existing fuel exports. In China and India there is an **existing methanol economy**, which on one hand could facilitate market uptake of CCU methanol but on the other could provide competition. It is possible that the petrochemical market in China could be **open to innovative production routes**, given the existing challenges with feedstocks, however the cost of renewables is higher in China and there may be a preference to valorise coal reserves.

7.2 Europe

Europe is dependent on fossil imports. The European Union has limited natural reserves and as domestic fossil-energy production is decreasing it is increasingly reliant on imports of primary energy commodities to satisfy its energy demand, with over half of energy needs covered by imports. This raises energy security concerns for the region. Russia is the EU's largest supplier, supplying approximately 40% of coal and natural gas imports and 30% of crude oil imports[128]. In Europe, Norway and the UK have the largest oil reserves. In 2018, the EU's primary energy production was dominated by renewable energy sources (34.2%) followed by nuclear energy (30.8%)[128].

Europe is expanding its renewable energy capacity, but costs for solar PV installations are high. Renewable energy capacity is increasing in Europe, with a growth of 24% since from 2015 to 2019. In 2019, installed renewables capacity in Europe was 575 GW, with Germany having the greatest capacity at 126 GW and the largest absolute increase since 2015 (27 GW)[121]. Spain, France, and the UK had the next largest

[126] GCCSI 2020, Global Status of CCS 2020 [LINK]
[127] IEAGHG 2018, Accounting for CO_2 Capture and Utilisation (CCU) Technologies – 2018 TR01c [LINK]
[128] Eurostat, Energy Production and Imports [LINK]

capacity at approximately 50 GW, with the UK having seen a 52% increase in installed capacity since 2015[121]. The EU has set targets to increase the renewables share of final energy consumption. The 2009 Renewable Energy Directive (RED) required that each nation had at least at 20% share of renewables in final energy consumption by 2020, with an overall EU target of 27% introduced for 2030[129]. Analysis by IRENA estimated that a renewable energy share of 34% could be achieved by 2030[130]. However, costs for installing solar PV in Europe have been consistently above the global average since 2017 and have plateaued in recent years. In 2020, solar PV installations commissioned in Europe had the highest commissioning price per MWh compared to other regions[122,123].

Europe has strong climate ambitions with established policy support systems.

- **Ambition:** In the European Green Deal the EU expresses aims to be climate neutral by 2050. In 2019 the UK enshrined net-zero emissions targets into law and there has been interest in implementing similar measures at the European level, with the target included in the proposed European climate law. The region has shown support for CCS projects. Europe has two large-scale operational CCS projects (Sleipner and Snøhvit in Norway) and a developing pipeline of projects focusing on industrial clusters, particularly in the UK, Netherlands, and Norway where there is access to storage in the North Sea. Several countries are also considering the use of renewable hydrogen as a prominent tool for decarbonisation of industry and transport.
- **Carbon pricing[145]:** The EU Emissions Trading Scheme (ETS) is a cap-and-trade system imposed on energy-intensive industries in all member states, as well as Iceland, Liechtenstein, and Norway. The value of carbon under the scheme currently averages around USD 19 /t CO_2. Many countries have also introduced additional carbon pricing policies as shown in Figure 13, with the highest carbon taxes in Sweden (USD 119 / t CO_2) and Switzerland (USD 99 / t CO_2). Other countries have worked to strengthen the ETS with an expansion of the sectors covered or a carbon price floor. Currently however there are no mechanisms that value or incentivise negative emissions, and it is unclear how CCU routes may benefit from the scheme. As part of the EU's Green Deal, discussions have commenced on the introduction of a carbon border adjustment mechanism for sectors at high risk of carbon leakage.
- **Funding:** Through Horizon 2020 and the Innovation Fund programmes, the European Union provides funding support both for early-stage research activities and for commercial demonstration of innovative low-carbon technologies. National and regional governments also have their own funding support initiatives, such as the UK Clean Growth Strategy, the Netherlands SDE++ scheme, and the Norwegian CLIMAT programme.
- **Policy and regulatory support:** In addition to carbon pricing mechanisms, the EU has policies to encourage the use of low-carbon fuels through the Renewable Energy Directive and Fuel Quality Directive. The updated RED II directive recognises renewable fuels of non-biological origin, such as CCU efuels, and also places upper limits on the use of biofuels produced from feed crops that can count towards targets set. The region has also implemented a range of policies aimed at lowering emissions from products, including product labelling and performance standards. Individual governments may also have procurement guidelines in place, such as minimum environmental assessment requirements or using a social carbon price to evaluate public projects.

A significant proportion of global CCU projects are located in Europe. According to analysis of the SCOT database, Europe accounts for 44% of global CCU research and development projects[131]. These are located primarily in Germany and the UK. Several of the routes investigated in this study had significant developments in the region:

- **CO_2 Cured Concrete:** The Carbstone concrete block product has been developed in Belgium and is expected to be available on the Belgium market soon.

[129] IRENA 2015, Renewable Energy Target Setting [LINK]
[130] IRENA 2018, Renewable Energy Prospects for the European Union [LINK]
[131] IEAGHG 2018, Accounting for CO_2 Capture and Utilisation (CCU) Technologies – 2018 TR01c [LINK]

- **Waste-To-Aggregates:** Developers include the UK based Carbon8 Systems, whose technology is deployed in the UK since 2012 and is due to be deployed at a site in France.
- **Methanol:** Iceland based Carbon Recycling International (CRI) is the leading developer for CCU methanol. In Europe, CRI have an established industrial plant in Iceland and commercial-scale plant under development in Norway. They are involved in research and development projects in Sweden and Germany. The company's 'Vulcanol' product is sold commercially to clients in Europe.
- **Polyols for Polyurethane:** Cardyon polyols are produced by Covestro at a small production facility in Germany and are marketed commercially in Europe.
- **Middle Distillate Hydrocarbons:** Sunfire (Germany) developed a CO_2 utilisation route for the production of synthetic crude. The technology is used at a pilot plant in Germany and is expected to be deployed as part of an industrial-scale project in Norway (Norsk e-fuel).
- **Synthetic Methane:** Small scale CO_2 to methane projects have existed in the region since the early 2010s, with many projects in Germany. There are now 4 larger scale (> 5 MW) planned or operational projects.

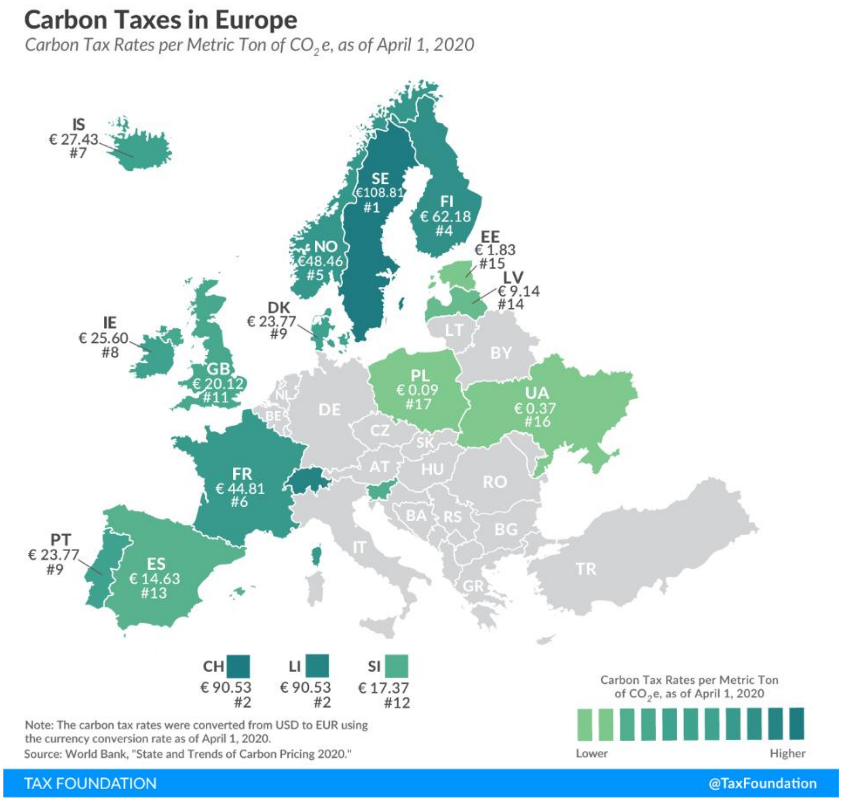


Figure 13: Carbon Taxes in Europe. Taken from TAX FOUNDATION webpage: https://taxfoundation.org/carbon-taxes-in-europe-2020/

Enablers for CCU in Europe are the strong climate ambitions (net-zero) and the policy & regulatory support encouraging the use of lower emission products or lower emission production routes. The region has good systems in place to foster low-carbon innovations through research funding and grants. The lack of fossil resources in the region could act as a driver to move towards a more circular use of raw materials and increase supply-security through replacing fossil feedstocks. The decrease of imports in favour of local production could also have benefits in terms of creating jobs. The barriers for CCU are the higher costs of renewables deployment and the need to prioritise renewables capacity for the transition to net-zero. There are also a number of established and accepted alternatives in the transport sector, limiting the market drivers for CCU transport fuels. In future, CCU chemical and polymer routes could be of particular interest to the region due to a combination of the current reliance on fossil imports, the lack of low-carbon alternatives and the net-zero ambition of the region. In the nearer-term, building material routes that treat waste residues may benefit from a business case in some countries with high waste-disposal costs. In general, CCU routes that are highly ambitious and aligned with significant emission reductions are likely to be favoured from a political perspective.

7.3 North America

North America is an exporter of fossil resources. The United States has reserves of coal, natural gas, and petroleum. The United States is historically a net exporter of these resources, but still relies on some imports to meet domestic demands. Canada has abundant natural resources, having the third largest proven oil reserves in the world and being the fourth largest producer of oil and of natural gas. Canada is a net exporter of natural gas, hydroelectricity, and crude oil with most exports going to the US[132].

Renewables capacity has increased in North America since 2015. Solar PV installation costs are low in the region. Installed renewables capacity in North America has increased by 27% since 2015 with capacity in 2019 at 390 GW, mostly from the United States (262 GW) and Canada (101 GW)[121]. Growth is mostly a result of increasing capacity in the United States (35% increase) with limited additions in Canada (6% increase)[121]. The cost of solar PV installations in North America is below the global regional average, with only the Middle East having a lower cost per MWh for commissions in 2019[124,125].

Climate ambition is inconsistent however a variety of support initiatives exist.

- **Experience:** The majority of global operational CCUS projects are located in the United States, primarily driven by revenues available for Enhanced Oil Recovery. The region also has several developing direct air capture projects, with the construction of the worlds largest DAC plant planned. The region has experience implementing the policy and contracting arrangements for CCUS.
- **Carbon pricing[145]:** In Canada, the federal government introduced a Pan-Canadian Approach to Pricing Carbon Pollution, prompting local governments to introduce their own carbon pricing initiatives or have the federal backstop (a regulatory charge on fuels per t CO_2 and output based pricing system) imposed. In the US, several bills for a carbon pricing system have been proposed at the federal level but none have yet made any legislative progress. In contrast, at the subnational level some states are co-operating to develop common ETS policies with others developing their own schemes. Mexico has a carbon tax covering all sectors and has commenced a pilot for an ETS scheme.
- **Funding:** The US Department of Energy has a number of distinct programmes to support CCUS, including programmes to support R&D, direct grants for projects, and the 45Q tax credit. These programmes have encouraged EOR and investment in negative emissions technologies. In Canada, there are several federal and provincial funding programmes that have supported CCUS projects, including the Clean Energy Fund (Government of Canada) and the Carbon Capture and Storage Fund (Government of Alberta). Canada has a Low-carbon and Zero-emissions Fuels Fund aimed at increasing the domestic production and adoption of low-carbon fuels.
- **Policy and regulatory support:** At the federal level, the United States has a Renewable Fuels Standard program and a voluntary product labelling scheme – the US Energy Star programme. The state of California has implemented a Low Carbon Fuel Standard, setting declining targets for emission intensity of fuel supplied in the state. Canada has introduced a similar Clean Fuels Standard requiring liquid fuel suppliers to gradually decrease the carbon intensity of the fuels produced or sold.

A significant proportion of global CCU projects are located in North America. According to analysis of the SCOT database, the United States and Canada account for 43% of global CCU research and development projects[133]. Several of the routes investigated in this study had significant developments in the region:

- CO_2 **Cured Concrete:** Developers include CarbonCure and Carbicrete which are both based in Canada, as well as Solidia Technologies based in the United States. CO_2 utilisation technology developed by CarbonCure has been deployed at many ready-mix concrete sites in the region.

[132] EIA 2020, Country Analysis Executive Summary: Canada [LINK]
[133] IEAGHG 2018, Accounting for CO_2 Capture and Utilisation (CCU) Technologies – 2018 TR01c [LINK]

- **Polyols for Polyurethane:** The Unites States based company November developed the CO_2 based polyols branded as Converge, which are now marketed by Saudi Aramco. Ford automakers tested the products for use in vehicle components with plans to include them in production lines.
- **Ethanol:** AirCompany, based in the United States, has developed a CO_2 to ethanol route based on electrochemical reduction, with the final product marketed and sold as Vodka in the region. In the past, Joule Unlimited Technologies developed a biological route for CO_2 to ethanol conversion.

An enabler for CCU in the region is the low cost of renewable electricity installations and the ability to install these at large capacities. This could provide a foundation for the production of low-cost hydrogen without impacting existing energy-systems. Another enabler is the region's experience with carbon capture projects and the associated introduction of CCUS funding support frameworks (e.g. 45Q tax credits). Challenges for CCU routes in the region are the easy access to competing fossil resources, the strength of the existing fossil fuel industry, and the lack of clear ambition in some states. The region is heavily market driven meaning that economically favourable CCU routes, such as those in polymers and building materials, are likely to perform well.

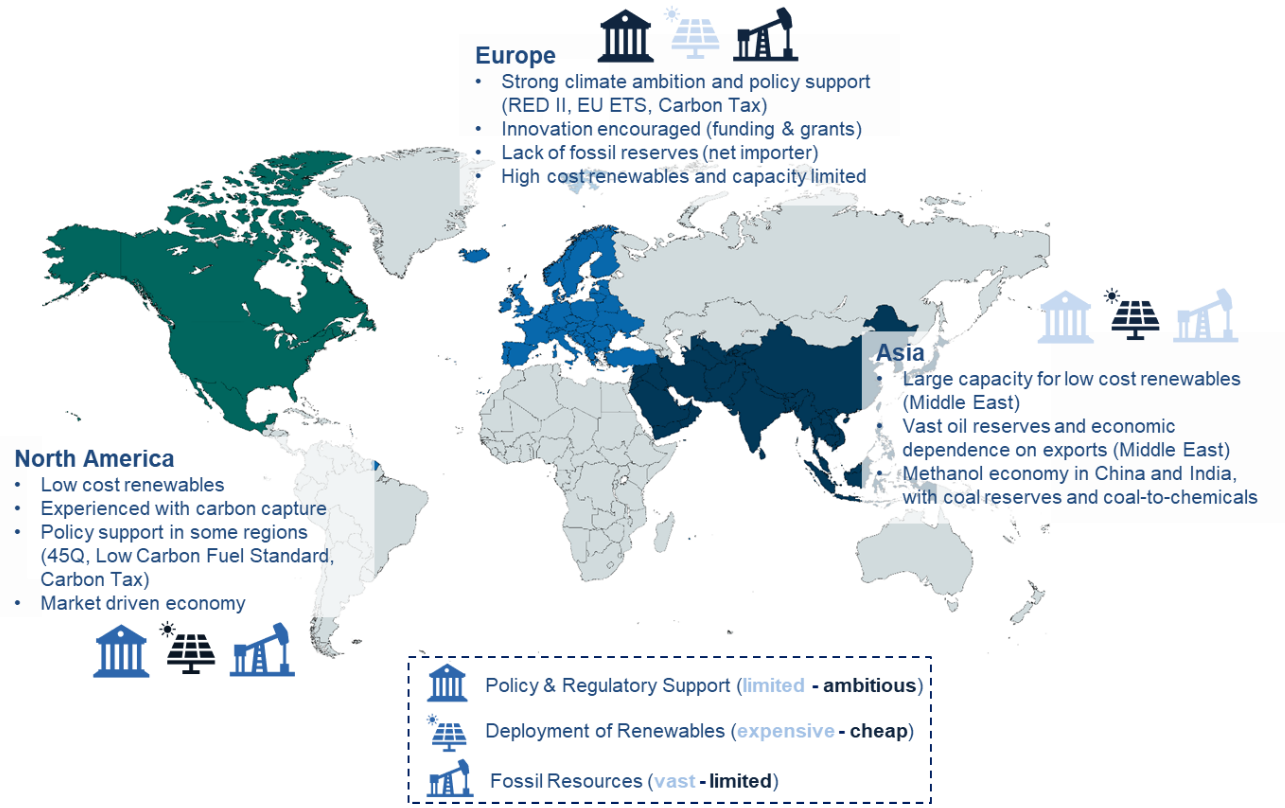


Figure 14: Summary of key regional factors influencing CCU.

8 Discussion & Conclusions

This study has evaluated a variety of CCU routes across materials, chemicals, fuels, and polymers to explore the strengths and weaknesses. The techniques for CO_2 utilisation varied, with some routes incorporating the entire molecule as a carbonate within polymers or building materials and others removing one or both oxygen atoms to transform CO_2 into a higher energy building block for fuels or chemicals. The scientific basis of these routes is mostly well-understood, although research is ongoing to optimise efficiencies, yields and to test suitability for new end-uses. In most cases there is also a strong knowledge of how the routes could feasibly be deployed at industrial scale, with prototypes developed and large-scale demonstrations planned or ongoing. Despite these factors, the level of further commercial development was variable and market interest uncertain. Several routes are currently not cost-competitive with conventional fossil-based production and therefore uptake is dependent on external drivers, such as carbon pricing or product mandates.

The following sections synthesise many of the key findings of our study. Section 8.1 shares the comparative assessment of the CCU routes analysed, section 8.2 outlines the key drivers, barriers and enablers, and section 8.3 provides recommendations for facilitating the development of CCU routes.

8.1 Comparative Assessment

Figure 15 illustrates the results of the comparative assessment of CCU commodities, using scores for each of the primary criteria to plot each (fully assessed) commodity. The overall findings are discussed below with the common strengths and weaknesses for each commodity category summarised in Table 6.

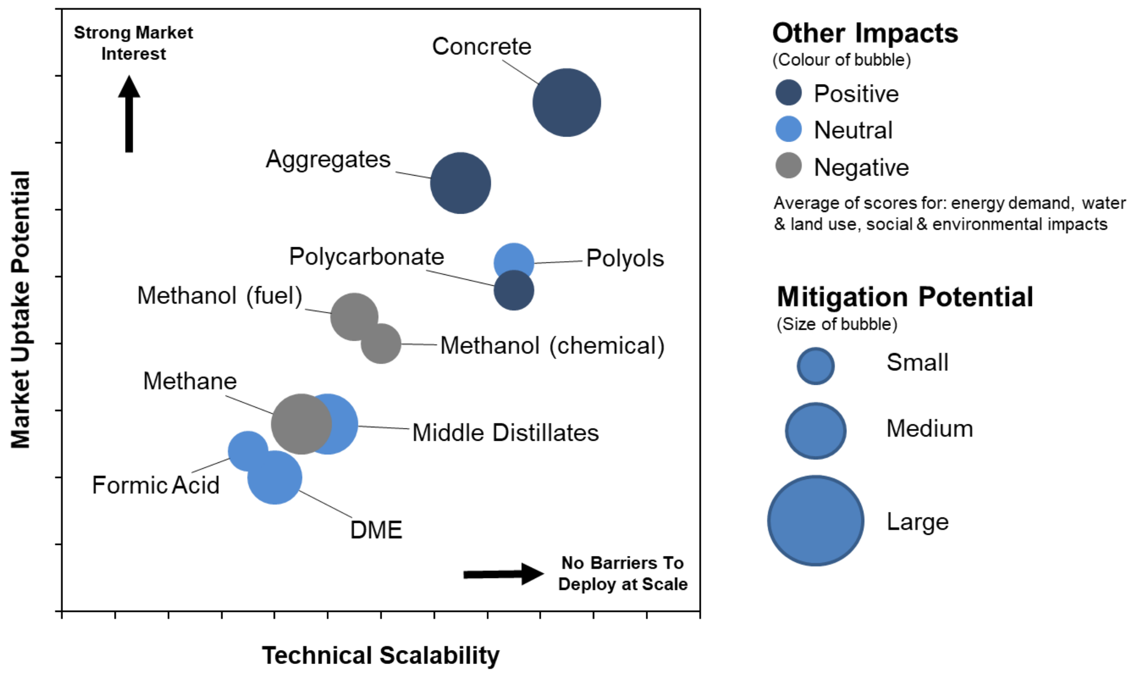


Figure 15 Summary of the comparative assessment outcome, highlighting the strengths and weaknesses of each commodity. Note that the relative position and size of bubbles represents the scoring performance, rather than absolute factors, such as market size, directly.

The mitigation potential, influenced by lifecycle emissions and market size, was greatest for building materials and fuels. CO_2 utilisation routes within these categories had clear potential for lower lifecycle emissions combined with a large addressable market (> 100 Mt product). Annual abatement levels greater than 1 Gt CO_2-eq could be achieved for direct replacement 'drop-in' fuels due to the substitution of 'new' fossil carbon with captured ('recycled') carbon. CCU fuels, however, face competition from alternative low-carbon energy carriers, such as hydrogen and electricity, and require low-carbon electricity during production to achieve lower emissions than conventional fossil-fuels. For building materials, annual abatement levels greater than 100 Mt CO_2-eq could be achieved, either via a reduction in the use of emission-intensive cement and/or via permanent sequestration of CO_2. The CCU building materials investigated are not thought to be energy-intensive in their production and some routes could offer negative emissions.

The mitigation potential of polymer and chemical routes was limited by the small markets for these products. Most of the CCU chemicals and polymers considered showed potential for lower lifecycle emissions per tonne of product, with the exception of some in earlier stages of development that require further optimisations. However, the addressable markets for each of the chemical and polymer products considered here ranged from 0.1-80 Mt of product, orders of magnitude smaller than those for fuels and building materials. For all routes besides methanol, this limited the mitigation potential to below 20 Mt CO_2-eq per year. The mitigation potential for methanol as a chemical intermediate could be considerably larger, both due to its existing market and the option for future market expansion, for example in olefin or DME production.

For fuels and chemicals, current market drivers for CCU are typically not sufficient to incentivise large scale market uptake. In most cases, CO_2 utilisation routes within the chemicals and fuels categories were found to be considerably more expensive than conventional fossil-based production routes. This largely resulted from high energy requirements for green hydrogen production, but also from the low yields and high catalyst costs of some of the lesser developed routes. Within the chemicals sector, the limited market drivers for CCU (improved sustainability, existing carbon pricing systems) are unlikely to be sufficient justification for the considerable cost premium currently incurred. Within the fuels sector there is greater political and regulatory support for sustainable products, with some regions introducing mandates or standards for the use of sustainable fuels. This could increase uptake of CCU fuels for those regions, provided the benefits of synthetic CCU fuels are recognized within the regulations. However, the cost-premium is still likely to be a considerable barrier to wide-scale deployment alongside other barriers in cases of indirect product substitution, such as fuel distribution and engine modification challenges.

The routes considered within building materials and polymers categories were found to have greater potential under existing market drivers. In these categories the CCU opportunities offered additional value propositions, such as cost savings or enhanced properties, with benefits from lowering emissions not necessarily being the focus for development. This has led CCU technologies to already be adopted in commercial settings. For building materials, CCU can offer cost reductions by lowering cement consumption or through the re-purposing of waste residues and avoidance of gate fees for waste disposal. For concrete, it may offer improved properties or production efficiencies. For polymers, raw material costs may be lower than the conventional route and energy requirements could decrease. It is possible that the different properties of CCU polyols may benefit certain end-uses. These routes are therefore not reliant on the emergence of new drivers for market uptake. Additional policy or regulatory support could, however, enable them to unlock additional value from having lower emissions than conventional products.

It was found that most routes had no significant technological barriers to scale production to reach the market potential. In the majority of the assessed routes, the technologies for CO_2 utilisation had been proven in a relevant environment or were expected to be composed of technologies that have been proven individually. Many routes had been demonstrated at an industrially relevant scale, and in the cases of CO_2-cured concrete, waste-to-aggregates, methanol, and BPA-PC technologies were ready for commercial deployment, such as via license agreement or delivery contracts. However, a key technical barrier for deployment of CCU fuels and chemicals at their maximum market potential could be the availability of low-carbon electricity for green hydrogen generation. For building materials, the distributed nature of concrete production could present challenges, the waste-to-aggregates route requires access to waste residues, and regulatory approval is needed for final products. For polymers, no significant barriers to production were identified, however non-identical products must be tested for their suitability for specific end-uses.

There is a wide array of potential co-benefits for the CCU routes. In addition to the emissions benefits of the CCU routes, a range of broader environmental and social benefits were also identified. A selection of these are highlighted below:

- **Re-use of waste residues:** The re-use of waste residues to produce building materials via CCU routes has benefits associated with the stabilization of the material, avoidance of land use for waste disposal, reduction in mining of primary aggregate, and potential recovery of valuable minerals. By stabilizing materials, this can prevent negative biodiversity and water contamination impacts caused by improper disposal. The avoidance of land-fill disposal and reduction in mining have benefits in terms of land-use and impacts on local communities. If valuable minerals can be simultaneously recovered, this allows for the benefit of lower depletion of primary mineral deposits.
- **Lower fossil resource consumption:** Within the chemicals, polymers, and fuels categories, CCU routes use captured CO_2 to substitute fossil-derived feedstocks to varying extents. Therefore, these routes avoid some of the issues associated with fossil extraction and distribution, such as their environmental impacts, supply uncertainties, cost volatilities, and social implications.
- **Safer chemical routes:** The use of CO_2 as a feedstock can offer alternative reaction pathways for routes that conventionally may use that toxic reagents or solvents. Other benefits may be a reduction in waste products in reactions.
- **Cleaner burning fuels:** Alternative fuels such as methanol, DME and ethanol have benefits of lower pollutants on combustion when compared to conventional diesel and gasoline fuels. This benefit is, however, mostly independent on how the alternative fuels are produced, whether CCU or conventional routes. There is potential that middle distillate fuels produced via the CCU Fischer-Tropsch routes could be cleaner burning than those produced by the conventional route.
- **Continued use of existing assets:** When compared to alternative low-carbon pathways, the use of CCU to produce conventionally fossil-derived products has benefits in that these identical products can feed in directly to existing supply chains. This allows continued use of existing assets (such as refineries, boilers, engines, distribution networks) and could be seen as a benefit from the perspective of retaining jobs and minimizing disruption. However, it should be noted that low-carbon alternatives will have their own advantages over CCU, which may outweigh this benefit.
- **Energy storage applications:** CCU can be used for the concept of Power-To-X in which renewable electricity is transformed into gaseous or liquid energy carriers, such as methane or methanol. This involves water electrolysis to produce hydrogen, itself an energy carrier, which can then react further with CO_2 to produce other products. This acts as a means for storing surplus renewable electricity.

However, there may be trade-offs, with impacts on land, energy, or water consumption. In many of the assessed routes there were trade-offs, with the CCU options performing worse for some environmental indicators compared to the counterfactual. For chemical and fuel routes, there was typically large increases in energy demand as energy input is required to convert stable CO_2 to a higher energy product. This was typically achieved via water electrolysis to produce hydrogen that would react with the CO_2. Therefore, these CCU routes often resulted in a considerable increase in water consumption, as well as increases in land-use with land required for deployment of renewable electricity generation.

Alternative low-carbon routes are also being developed within the categories considered here. The focus of this study was to highlight the progress, drivers, and barriers of a selection of CO_2 utilisation opportunities. It is important, however, to emphasize that although CO_2 utilisation may be seen as one route to lowering emissions, there are often other alternative pathways to lowering emissions. For example, there are bio-based routes for the production of some chemicals, fuels, and polymers. For fuels, electrification and hydrogen are becoming established alternatives for both transport and heating applications. There are also options to lower emissions of conventional routes, such as fuel-switching or carbon capture and storage, or in some cases negative emission technologies could be implemented to offset emissions. Whilst this report has referred to competitive options in places, to properly compare CCU routes to these alternatives a more detailed holistic analysis would be required for individual routes.

The common strengths and weaknesses identified within each commodity category are summarised in Table 6. The strengths column shows the sub-criteria in which the CCU routes within the category tended to score highly, and the weaknesses/limitations columns highlights the sub-criteria where their scores were lower. An explanation of the sub-criteria can be found in section 2.2. A more detailed discussion on the common strengths and weaknesses for each category is included in each of the previous category chapters, chapters 3-6, where more detail is also given for individual CO_2 utilisation routes.

Table 6: Common strengths and weaknesses (or limitations) for CCU routes within each of the commodity categories investigated.

Category	Strengths	Weaknesses / Limitations
Building Materials	CCU routes performed well across all sub-criteria, with strongest areas being: Cost & value proposition Emissions avoided (per tonne) Current TRL Competitive low carbon options	Policy & regulatory factors Technical deployment factors
Polymers	Cost & value proposition Emissions avoided (per tonne) Technical deployment Social & environmental Impacts	Total addressable market Technology development
Chemicals	Emissions avoided Competitive low carbon options	Cost & value proposition Policy & regulatory factors Energy consumption Technical deployment factors
Fuels	Emissions avoided (per tonne) Total addressable market Current TRL Social & environmental Impacts	Competitive low carbon options Policy & regulatory factors Energy consumption

8.2 CCU Drivers, Barriers & Enablers

CO_2 utilisation opportunities are diverse, and each route has its own specific drivers, barriers, and enablers. This study has assessed a broad range of CCU routes and has highlighted the diversity in motivations for CCU development, alongside the variety of barriers encountered and range of enabling options. Some routes may be driven by opportunities to reduce costs, whereas other routes encounter cost premiums as a key barrier. In some cases, a reduction in emissions is a key driver for CCU developments, whereas in others this is more an added bonus. A variety of specific barriers were identified such as failings of regulations to recognise CCU fuels as sustainable options, the conservative nature of the construction industry, and the limited lifetimes and expensive nature of novel catalysts. The enablers for CCU routes were similarly diverse, with waste-to-aggregates enabled by high gate-fees for waste-disposal and polyols potentially enabled by characteristics of the existing polyol market. Specific drivers, barriers, and enablers of CCU routes are discussed in more detail within each of the commodity category chapters, Chapters 3-6.

There are, however, some common drivers, barriers and enablers that span across many of the CCU routes assessed. Although the assessed routes were diverse and covered a broad set of applications, there are some general themes that are common for many CO_2 utilisation pathways. The drivers, barriers and enablers can be categorised into those relating to regulatory or policy factors, those relating to technical factors for the route or for deployment, and those relating to market or economic factors, including product competitiveness and market perceptions.

Regulatory and Policy

Regulations such as mandates or standards could act as drivers for the uptake of CCU products and enable their development by increasing demand. The introduction of legal requirements for manufacturers or firms to supply or procure a minimum percentage of products from sustainable or low-emission sources can have the impact of increasing demand for these products. Examples of existing regulations for fuels include the EU Renewable Energy Directive (RED II), which requires 14% of energy consumed for road and rail transport to be of renewable origin by 2030, and the California Low Carbon Fuel Standard, which has set declining targets for the carbon intensity of fuels supplied in the state. Environmental standards can also be applied in the construction sector, with requirements on new buildings to achieve certain ratings in environmental assessments, including embedded carbon. If CCU products are recognised in such regulations and standards then this can offer them a more viable route to market, providing they are competitive with other sustainable options, and the existence of such a market could foster further CCU innovations.

However, prescriptive regulations can act as a barrier to CCU uptake. Existing standards and regulations may restrict the uptake of CCU products in the market. For example, most fuel quality standards restrict the level of methanol blending in motor gasoline, limiting blending to 3% by volume in Europe and 5% in the United States[134]. However, trials have shown methanol blends of 15% (M15) to be suitable for standard combustion engines and M15 blends are already used extensively in China[135]. In the construction sector, compliance with standards and codes is typically prescriptive on material composition rather than performance, inhibiting for example the use of novel cements. Regulations, such as EU End of Waste, can also prohibit the use of waste material in commercial products. In addition, CCU routes may be unable to access existing benefits aimed at encouraging sustainable options due to the use of prescriptive descriptions that inadvertently exclude CCU products. For example, sustainable fuel standards that specifically target biofuels or regulations requiring dedicated renewables as inputs rather than specifying a calculated carbon intensity of fuel.

As with many emerging technologies, financial support can facilitate the development of CCU technologies. Similar to CCS projects and other low-carbon technology development, the development, demonstration and uptake of CCU technologies can be facilitated by financial support from governments or institutions. The EU Horizon 2020 programme has provided funding to a range of CCU technology developers and researchers, including a EUR 1.8 million grant to Carbon Recycling International to scale-up its technology[136] and EUR 50,000 grant to Carbon8 Systems for a feasibility study investigating market and legislative conditions[137]. The UK government has a funding programme for the design and construction of CCU demonstration projects[138]. In the United States, the 45Q tax credit, enacted in 2018, offers a tax preference for the qualified use of CO_2 or its geological storage. This is mostly expected to encourage the use of CO_2 for enhanced oil recovery, however the associated infrastructure expansion could also benefit other CCU applications[139].

CCU uptake would be enabled by policies to level the field by recognising sustainability benefits. CCU products are typically not cost-competitive with incumbent products and this acts as a key barrier for market uptake. Policies that allow CCU products to realise value from their sustainability benefits would enable CCU products to be more competitive in the market. For example, carbon pricing mechanisms, such as a carbon

[134] IEA AMF webpage on Fuel Information: Methanol [accessed Jan 2021] [LINK] (5% blend in the US using the "Octamix" waiver requires a minimum of 2.5% of co-solvents)
[135] Methanol Institute 2019, Overview of Global Methanol Fuel Blending [presentation] [LINK]
[136] https://cordis.europa.eu/project/id/848757
[137] https://cordis.europa.eu/project/id/856282
[138] https://www.gov.uk/government/publications/carbon-capture-and-utilisation-demonstration-ccud-innovation-programme
[139] IEA 2019, Putting CO_2 To Use

tax or emissions trading scheme, or other policy support schemes such as a Contract for Difference style mechanism. A range of policy support mechanisms relevant to CCU are discussed in Box 3.

There is a lack of understanding of the benefits of CCU and a lack of clarity on how these benefits may be realised through carbon accounting. The benefits of CCU can be calculated through comparative lifecycle assessments, however the comprehension of such assessments can be challenging, particularly as results can vary considerably depending on the assumptions used. This makes it difficult for policy makers to assess the benefits of CCU technologies and enact appropriate support mechanisms. Furthermore, there is a lack of consensus on the accounting of utilised CO_2, how carbon removal technologies could be awarded carbon credits or similar benefits, and how future carbon accounting frameworks might be implemented for globally traded products. This uncertainty may act as a barrier both for technology adopters, wanting to market the benefits of their products, and adopters/consumers that may need to account emissions.

The accounting of CO_2 through monitoring, reporting, and verification is important but has many challenges. Accurate accounting of CO_2 is important for keeping track of progress towards climate targets and is needed for the successful application of policy mechanisms such as carbon pricing. Challenges in CO_2 accounting can relate to: the technical determination of CO_2 emissions within a process; the tracing of emissions from feedstocks; the suitable allocation of these emissions and the division of responsibilities; and challenges related to how political frameworks might be applied and how they might work across borders. CO_2 utilisation has particular challenges due to the potential re-use of captured CO_2 and the variable sequestration times. Information on CO_2 accounting for CCU routes is available in the IEAGHG's 2018 'Greenhouse Gas Emissions Accounting for Carbon Dioxide Capture and Utilisation (CCU) Technologies' reports[140,141].

Box 3: Policy Support Mechanisms For CCU*

Operational subsidies can be used to lower the relative cost of CCUS operations either at the capture facility or for the producer of low-carbon products. Examples of operational subsidies are the Contract for Difference mechanism and a Tax Credit mechanism:

- **Contract for difference (CfD):** The low-carbon producer is compensated the cost differential between the cost of producing their product and an agreed strike price, often based on a market reference (such as the CO_2 price). This acts as an operational subsidy enabling low-carbon products to be sold at competitive market prices. It can also facilitate the obtainment of capital costs by providing investors with the market certainty needed to invest in emerging technologies.
- **Tax credits:** Companies receive a reduction in the tax liability for fulfilling specific criteria, such as producing low-carbon products or capturing / abating emissions. For example, 45Q in the United States.

Carbon pricing mechanisms can be used to charge companies a price for their emissions, providing an economic advantage to lower emission production routes. These mechanisms could charge for all emissions above a base level, such as a carbon tax, or they could use a tradable market mechanism, such as the EU ETS, in which companies are allocated emission allowances that can be traded. Carbon removal credits have been proposed as an extension to these mechanisms, which could apply to CCU projects using DAC with permanent sequestration.

Capital support such as grants or loans from governments can be used to fund research, construct demonstration projects, or bring products to market. Grant support has facilitated the deployment of many

[140] 2018-TR01a – Characterizing CCU Technologies, policy support, regulation and emissions accounting
[141] 2018-TR01b – Greenhouse Gas Accounting Guidelines for CCU

early CCUS projects, such as the Boundary Dam Coal Power Station in Canada, and has also funded CCU demonstration projects.

Loan guarantees involve a guarantee from the government to provide debt finance in the case that project costs overrun. They are a type of risk mitigation mechanism that can facilitate the deployment of emerging technologies by increasing investor confidence through reducing their exposure to financial risk.

Low carbon standards / obligations can be used to mandate the development, supply, or use of lower emission products. A common example are fuel standards requiring suppliers to supply a percentage of fuels from sustainable sources. Provided these standards accommodate CCU products, they can enable a higher market price for CCU products.

Demand side measures can be used to increase the market demand for lower emission products, driving developments and achieving economies of scale by allowing developers to deploy at larger scales. Examples of demand-side measures are procurement and certification/product labelling:

- **Procurement:** Procurement rules or guidelines can be used to encourage the use of lower emission products or services. Governments can use public procurement rules to set minimum standards for public projects or to allow tenders that have higher levels of emission mitigation ambition to have a competitive advantage. In addition, governments could work to develop sustainable procurement guidelines that may be used more widely by private companies. Another option is for governments or state-owned entities to themselves procure low-emission projects.
- **Certification/product labelling:** Certification schemes can allow sustainable or lower-emission products to receive certified recognition of their benefits and thus give confidence to consumers. Certifications can be used alongside procurement guidelines to facilitate decision making in the market. Product labelling can be used to increase awareness of a product's environmental impacts.

*This box details some policy mechanisms that could support CCU however it is not intended to be a comprehensive list of options available. These mechanisms were identified within the course of the study as possible support mechanisms. Assessment of their effectiveness was outside the scope of the study.

Reference: IEA 2020, CCUS Policy Measures

Technical

CCU developments can be driven by environmental motivations, such as emission reductions, the recycling of CO_2**, and the avoidance of fossil feedstocks.** These benefits are often cited as motivations for developing CCU routes, with the majority of routes assessed here offering reductions in CO_2 emissions over their counterfactuals. Circular economy principles of re-using CO_2 and avoiding the extraction of raw materials are also key drivers for technology development, particularly in the chemicals and polymers sectors where carbon is a vital building block.

CCU can also be driven by opportunities to improve production methods or create new or enhanced products. There are examples in which CCU was adopted partially because the production route was superior to existing processes, for example by avoiding toxic reagents, lowering resource consumption, eliminating waste products, or improving efficiencies. Some CCU routes, such as CO_2 cured concrete, polyols, and synthetic fuels, may produce products that offer superior properties to conventional products.

Coordination of CCU with wider system factors can be an enabler. CCU could be enabled through industrial symbiosis, where industrial players coordinate to optimise material flows. CCU routes can benefit from the co-location of emitters and utilisers, with proximity offering the chance to use lower-purity CO_2 in routes that have this option, thereby reducing costs. An interesting example is the application of the waste-to-aggregates route at cement sites as this uses both waste-residues and flue gases directly from the cement plant and produces a product (aggregate) that is relevant to the sites existing markets[142]. CCU may also benefit from sharing infrastructure with CCS projects focussed on industrial clusters, or alternatively CCU may act to facilitate CCS by providing an early destination for captured CO_2. Some CCU developments may be driven by Power-To-X (PtX) motivations, with CCU considered a method of storing surplus renewable electricity and reducing overall costs of energy provision[143]. PtX also allows the delivery of renewable energy via alternative energy vectors, which may be easier to integrate with existing distribution routes[143].

Further RD&D is required for some routes at low TRL to overcome technical obstacles. CCU routes at earlier stages of development require further research to optimise processes, with some identified focus areas relating to increasing yields, catalyst development (improving lifetime, selectivity, cost, and availability), lowering energy consumption or facilitating product separation. Once a process is optimised, CCU routes must undergo subsequent development steps, such as demonstration in a relevant environment and at-scale demonstration, before they are considered ready for commercial uptake. In addition to technical developments, improved reporting and access to data required for lifecycle and economic assessments would enable a better understanding of the benefits and challenges for CCU routes.

Product testing requirements and the conservative nature of some markets may act as barrier to CCU. The difficulty of approving and integrating CCU products into markets is likely to depend upon whether or not the final product is identical in composition and properties to an existing product. Identical products, such as chemicals, could be sold directly into existing supply chains if they are shown to meet required standards, such as chemical identity and purity. However, new products need to undergo testing to demonstrate their suitability for the intended applications before they are approved and can be deemed acceptable by industry. For example, novel fuels must undergo extensive testing and gain warranties from engine manufacturers before they can be deemed suitable for existing engines. This is typically a lengthy and expensive process, particularly in the case of aviation fuels where large production volumes are needed for testing. The conservative nature of some markets may also act as a barrier, requiring significant trials to build market confidence.

Technology uptake is enabled by straight-forward set-ups, using well-understood processes, or allowing for flexibility in production. Technology deployment may be facilitated by straightforward set-ups, such as containerised or modular systems, and the use of processes that are well-understood and easily engineered. The ability to use lower purity CO_2 could be an enabler, as well as the ability to vary operating times, for example to link to a variable electricity supply or work alongside existing production patterns.

Market and Economic

Company sustainability targets could lead to interest in CCU. An increasing number of companies are setting climate targets and incorporating sustainability considerations into their ambitions. As companies gain awareness of upstream emissions, these targets could lead them to consider alternative lower-emission production routes in their supply chains. Recently Unilever announced its ambition to replace 100% of the carbon in its cleaning and laundry formulations with renewable or recycled carbon by 2030, of which captured CO_2 is listed as one of the potential sources for chemicals[144]. Alongside this ambition the company announced a fund of EUR 1 billion to finance biotechnology research, CO_2 and waste utilisation, and low carbon chemistry.

The cost of CCU routes can be a key barrier to their adoption. However, a select few routes are driven by cost-savings or improving the value of products. In markets for primary materials or essential commodities, product costs are often the most important selection factor. CCU routes for chemicals and fuels currently can have much higher production costs than their counterfactuals. Estimates have suggested that CCU methanol and formic acid would be at least 2 and 2.5 times as expensive respectively[68,74]. These cost premiums are unacceptable for the current market, acting as a significant barrier to market uptake. Conversely

[142]Carbon8 Systems 2020, Press Release: Carbon8 Systems to deploy its pioneering technology at Vicat Group cement company in France [LINK]
[143] Siemens 2020, Power-to-X: The crucial business on the way to a carbon-free world [LINK]
[144] Unilever 2020, Press Release: Unilever to eliminate fossil fuels in cleaning products by 2030 [LINK]

there are examples of CCU routes within building materials having a business case today based on economic factors, and it feasible that polymer routes could also offer lower costs than their counterfactuals.

Avoidance of fees or compliance with regulations could become a driver if more ambitious incentives or targets are imposed. The potential for CCU routes to have lower emissions than counterfactuals offers the opportunity for carbon pricing mechanisms to lower cost premiums. The parallel study, "Reality Check: CO_2 Hydrogenation", estimated that, for methanol, formic acid and middle distillate hydrocarbons, cost parity with existing counterfactual prices could be achieved in the long-term by implementing a 'cost of emissions' of USD 150-225 / tCO_2-eq. At this point, market uptake could be driven by economic factors. These values are more ambitious than most current carbon prices, almost half of which fall below USD 10 / tCO_2-eq but are highest in Sweden at USD 119 / tCO_2-eq[145]. Alternatively, market uptake of sustainable products could be driven by a need to comply with imposed targets or regulations. For example, many countries in the EU have set obligations for biofuels incorporation in gasoline and diesel, ranging from 5% of fuel energy in Cyprus to 20% in Finland[146]. Norway has set a quota for 0.5% of aviation fuel to be sustainable in 2020 rising to 30% in 2030[147].

A lack of awareness or engagement with product lifecycle emissions and/or a lack of awareness of CCU can act as a barrier. To date, most companies have focused efforts on reducing direct emissions, such as fuel combustion, and emissions from purchased electricity and heat supplies (Scope 1 and Scope 2)[148]. Manufacturers do not have direct ownership or control over the emissions in their supply chain or the end-use of their products (classed as Scope 3), meaning they may not consider themselves responsible for these emissions or may not be able to obtain data on these emissions[148]. This lack of interest or awareness of indirect emissions may act as a barrier to CCU developers producing intermediate goods. Furthermore, the lack of commercial development, clarity, and marketing of CCU may mean that engaged companies opt for the more 'obvious' sustainable options, such as bio-based products.

Consumer perception could be a barrier, if not managed well, or a driver. The concept of CCU may not be perceived positively by consumers, who may have unfounded concerns about the use of CO_2 in products. For example, they may associate CO_2 with being hazardous, have concerns over product quality, or not trust claims that the product is sustainable[149]. On the other hand, careful marketing could allow products to use sustainability as a selling point, similar to the marketing of bio-based products.

8.3 Recommendations

Based on the drivers, barriers and enablers identified, the following summary of recommendations can be made to enable improved understanding, further development, and facilitate uptake of appropriate CO_2 utilisation opportunities:

- Researchers should focus on ensuring routes are practical to implement at scale, such as by using well-known pathways or equipment, accessible and low-cost catalysts, being energy efficient and allowing for flexibility in renewable energy supply and/or the purity of CO_2.
- Researchers should report sufficient data to allow for LCA and TEA analysis, and this subsequent analysis should follow guidelines to help with alignment of the methodology and comprehension of the results by non-experts.
- Further work is needed to highlight priority areas for CCU development, with a particular emphasis on identifying end-uses where CCU is expected to be a necessary component of future decarbonisation pathways. This could involve a holistic assessment of specific CCU pathways against a range of low-carbon alternatives, including consideration of future availability and whole system impacts.

[145] World Bank Group 2020, State and Trends of Carbon Pricing 2020 [LINK]
[146] ePURE webpage: Overview of biofuels obligations in the EU [accessed Jan 2021] [LINK]
[147] https://www.regjeringen.no/en/aktuelt/mer-avansert-biodrivstoff-i-luftfarten/id2643700/

[148] Science Based Targets, Navigant, and Gold Standard 2018, Value Change in the Value Chain: Best Practices in Scope 3 Greenhouse Gas Management [LINK]
[149] Arning et al. 2017, Risk perception and acceptance of CDU consumer products in Germany [LINK]

- Researchers, institutions, and manufacturers can work to improve awareness of lifecycle emissions for existing products, engage with the public and with policy makers, and improve understanding of the benefits and limitations of CCU routes.
- Manufacturers should increase their own awareness of upstream emissions in their supply chains and identify opportunities to switch to more sustainable production routes. A consortium approach could facilitate this with companies working together to increase awareness, demand more from suppliers or fund their own research initiatives.
- Policy makers can work to enable CCU by introducing support mechanisms that allow CCU to receive recognition for sustainability benefits and compete on a more level-playing field with conventional products. The introduction of an ambitious carbon pricing mechanism which incorporates CCU is one option for this; a summary of select policy options can be found in Box 3.
- Policy makers and regulators should ensure that CCU products are incorporated appropriately into existing support schemes, regulations, and product standards. For example, by moving to performance-based standards rather than prescriptive requirements.
- Governments can encourage innovations and developments in CCU by providing funding for research programmes and demonstration projects, or through other support mechanisms.
- Further work is needed to develop and clarify frameworks for the carbon accounting of CCU routes, considering how emission benefits can be recognised, the implications for globally traded products and an inclusion of negative emissions accounting.

*This study was developed in parallel with '**CO_2 Reality Check: Hydrogenation**', which provides a more detailed look at factors impacting the mitigation potential, costs, and energy demands of methanol, middle distillate hydrocarbons, and formic acid. This parallel study also highlights implications of some of the CO_2 accounting challenges and discusses additional motivations for CCU. Many readers may find it useful to read the studies together to provide complementary information and perspectives.*

Appendix: Scoring of Sub-Criteria

Emissions Avoided (per tonne)

Score	Description
1	The CCU process results in significantly more GHG emissions than the counterfactual route.
2	The CCU process results in slightly more GHG emissions than the counterfactual route.
3	The CCU process results in similar GHG emissions than the counterfactual route.
4	The CCU process results in somewhat less GHG emissions than the counterfactual route.
5	The CCU process results in significantly less GHG emissions than the counterfactual route.

Total Addressable Market

Score	Description
1	Greater than 1 Mt of product today
2	Greater than 10 Mt of product today
3	Greater than 100 Mt of product today
4	Greater than 1 Gt of product today
5	Greater than 10 Gt of product today

Competitive Low Carbon Options

Score	Description
1	There are well established low carbon alternatives that are expected to limit market uptake.
2	
3	There may be alternative low carbon technologies however these are either not yet well established or face limitations on the percentage of the market that they could penetrate.
4	
5	The technology has a distinct purpose that is not threatened by alternative low carbon technologies.

Cost & Value

Score	Description
1	The technology is not cost-competitive. This is a major barrier for market demand.
2	The technology is not cost-competitive. This is a significant barrier for market demand.
3	The technology is unlikely to be cost-competitive with the counterfactual however drivers exist to place extra value on the route within the market (justifying payment of cost-premium)
4	There is a a good business case for use of the technology resulting from cost savings or other added value (e.g improved performance)
5	There is a strong business case for use of the technology resulting from significant cost savings and additional value propositions

Commercial Development

Score	Description
1	The technology has not been demonstrated at a pilot scale
2	The technology is at demonstration stage with possible market interest
3	The technology is at a demonstration stage with clear evidence of market interest (e.g. partnerships or trials with established market players or end-users)
4	The technology is being used commercially with licensing or technology delivery contracts in place
5	The technology has been adopted by market players and is used commercially at multiple sites

Current TRL

Score	Description
1	Technology not yet validated in relevant environment.
2	Technology demonstrated but not applied to specific CCU production route **and/or** technology validated in relevant environment
3	Pilot demonstration of CCU route
4	Large scale or commercial demonstration of CCU route
5	Commercial deployment of CCU route

Policy & Regulatory Factors

Score	Description
1	The route requires additional policy or regulatory support to be successful.
2	The route requires additional policy or regulatory support to be successful. Similar support or regulations exist in the market.
3	Success of the route may be reliant on the existence of specific policy or regulatory factors which already exist in some regions. Updates to existing policy or regulations may be needed to enable scale-up or market uptake.
4	The route can succeed with existing policy and regulations, however additional support would benefit scale-up and market uptake.
5	The route can be successful using the existing policy mechanisms available and the existing regulatory system

Technical Deployment Factors

Score	Description
1	
2	Deployment of the technology requires significant engineering (e.g. new facility to be built) which incur challenges (e.g. due to novelty). There may be limitations on location or due to resource requirements.
3	Deployment of the technology requires significant engineering (e.g. new facility to be built) however the engineering requirements are similar to conventional routes. There may be limitations on location or due to resource requirements.
4	Deployment of the technology is mostly simple however there may be minor limitations due to location or resource requirements **and/or** the technology can drop-in to existing production with modifications to processes required.
5	Deployment of the technology is simple with no limitations of location or resource requirements **and/or** the technology can drop-in to existing production.

Energy Demand

Score	Description
1	The CCU process results in significantly higher energy consumption than the counterfactual route.
2	The CCU process results in slightly higher energy consumption than the counterfactual route.
3	The CCU process results in similar energy consumption to the counterfactual route.
4	The CCU process results in somewhat lower energy consumption than the counterfactual route.
5	The CCU process results in significantly lower energy consumption than the counterfactual route.

Water & Land Use

Score	Description
1	There is a significant increase in either land or water consumption.
2	There is an increase in either land or water consumption.
3	Land and water consumption is similar to the counterfactual route **or** one factor has a slight increase and the other a slight decrease.
4	There is a decrease in either land or water consumption. Neither land nor water consumption increases.
5	There is a significant decrease in either land or water consumption. Neither land nor water consumption increases.

Environmental & Social Impacts

Score	Description
1	Additional impacts are mostly highly negative.
2	
3	
4	
5	Additional impacts are mostly highly positive.

Evaluating technology options to mitigate greenhouse gas emissions

IEA Greenhouse Gas R&D Programme

Pure Offices, Cheltenham Office Park, Hatherley Lane,
Cheltenham, Glos. GL51 6SH, UK

Tel: +44 1242 802911

mail@ieaghg.org
www.ieaghg.org