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THE POTENTIAL OF CARBON UTILISATION IN A NET ZERO EMISSION ECONOMY

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PREFACE

This report has been produced by the International Centre for Sustainable Carbon (ICSC) and is based on a survey and analysis of published literature and on information gathered in discussions with interested organisations and individuals. Their assistance is gratefully acknowledged. It should be understood that the views expressed in this report are our own and are not necessarily shared by those who supplied the information, nor by our member organisations.

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ABSTRACT

Achieving net zero emissions (NZE) requires diverse approaches for different sectors and a broad suite of technologies including electrification, hydrogen, sustainable biofuels and carbon capture, utilisation and storage (CCUS). More countries are relying on CCUS in their long-term climate change mitigation policies. Led by Europe and North America, several countries have developed comprehensive legal and regulatory frameworks and provided significant funding and investment incentives for CCUS, while policies on climate and/or CCUS are advancing or being considered in others. Recent investment incentives and ambitious climate targets are building momentum for CCUS, resulting in many new projects being announced globally.

Technologies for converting recycled carbon dioxide (CO_2) into a value-added product are attracting increasing interest for their potential role in emissions mitigation and in a circular NZE economy. Carbon capture and utilisation (CCU) covers a wide variety of technologies and processes with varying levels of technical and commercial maturity, and differing mitigation potential across a range of applications. A matrix of CCU technologies for the production of commercially established products including chemicals, fuels, polymers and building materials, has reached the commercialisation or demonstration stage. Commercial plants are operational in different parts of the world transforming captured CO_2 into fuels and chemicals, and more projects are in development. There is a wide range of products based on CO_2-derived polymers that are essential in daily life in the commercial market. Hundreds of concrete plants in America, Asia and Europe are adopting a CO_2-curing process. Several plants are manufacturing building materials from the carbonation of industrial wastes with captured CO_2, and the list goes on.

CCU can provide climate benefits by displacing an equivalent product with higher life-cycle CO_2 emissions such as fossil-based fuels, chemicals, or conventional building materials. With its versatility of application and demonstrated effectiveness, CCU is a necessary element of the technology suite that must be deployed if the world is to achieve NZE. This report reviews the latest developments in CCU, including CCUS-related national and regional policies and regulations and the status of CCUS. Progress in CO_2 conversion technologies and applications is described and the potential role of CCU in achieving the NZE goals in a circular economy is assessed.

ACRONYMS AND ABBREVIATIONS

A2F	air to fuels
ACT	Accelerated Carbonisation Technology
APCr	air pollution control residues
CBAM	Carbon Border Adjustment Mechanism
CCS	carbon capture and storage
CCU	carbon capture and utilisation
CCUS	carbon capture, utilisation and storage
CE	Carbon Engineering
CEQ	Council on Environmental Quality, USA
CMU	concrete masonry unit
CRI	Carbon Recycling International
CUT	Carbon Upcycling Technologies
DAC	direct air capture
DOE	Department of Energy, USA
EC	European Commission
e-fuels	renewable synthetic fuels
EOR	enhanced oil recovery
EPA	Environmental Protection Agency, USA
EPBC Act	Environment Protection and Biodiversity Conservation Act 1999 (Cth), Australia
ETL	emissions-to-liquids
ETS	Emissions Trading Scheme
EU	European Union
FID	Final Investment Decision
FT	Fischer-Tropsch
FYP	Five-Year Plan
HZI	Hitachi Zosen Inova
GHG	greenhouse gas
ICSC	International Centre for Sustainable Carbon
IEA	International Energy Agency
IGCC	integrated coal gasification combined cycle
IPCC	Intergovernmental Panel on Climate Change
IPCEI	Important Project of Common European Interest
IRA	Inflation Reduction Act, USA
LCA	life cycle analysis
LNG	liquefied natural gas
MCi	Mineral Carbonation International
MENA	Middle East and North Africa
METI	Ministry of Economy, Trade and Industry, Japan
MHI	Mitsubishi Heavy Industries
MSW	Municipal solid waste

NDCs	Nationally Determined Contributions
NEDO	New Energy and Industrial Technology Development Organisation, Japan
NZE	net zero emissions
P2X	Power-to-X
PEM	proton exchange membrane
R&D	research and development
RD&D	research, development and deployment
RWGS	reverse water-gas shift
SAF	sustainable aviation fuels
SCALE Act	Storing CO_2 and Lowering Emissions Act, USA
SDGs	Sustainable Development Goals, UN
TES	Tree Energy Solutions
TIER	Technology, Innovation and Emissions Reduction Regulation
UN	United Nations
UNFCCC	United Nations Framework Convention on Climate Change
USE IT	Utilizing Significant Emissions with Innovative Technologies Act, USA

Note: all monetary values are in United States dollars ($) unless otherwise stated.

UNITS

d	day
Gt	gigatonnes
$GtCO_{2\text{-eq}}$	gigatonnes of carbon dioxide equivalent
$GtCO_2/y$	gigatonnes of carbon dioxide per year
Gt/h	gigatonnes per hour
GW	gigawatt
GWh	gigawatt-hour
kt	kilotonnes
kt/y	kilotonnes per year
$ktCO_2/y$	kilotonnes of carbon dioxide per year
L	litre
m^3/h	cubic metre per hour
ML	million litre
MW	megawatt
MWe	megawatt electric
tCO_2/d	tonnes of carbon dioxide per day
tCO_2/y	tonnes of carbon dioxide per year

CHEMICALS

CH_4	methane
CO	carbon monoxide
CO_2	carbon dioxide
$CO_{2\text{-eq}}$	carbon dioxide equivalent
DMC	dimethyl carbonate
e-gas	synthetic methane using renewable electricity
e-NG	synthetic natural gas using renewable electricity
H_2	hydrogen
H_2O	water
MEG	monoethylene glycol
PHB	polyhydroxybutyrate
PLGA	polylactic-co-glycolic acid
SO_2	sulphur dioxide

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EXECUTIVE SUMMARY

To achieve net zero emissions (NZE) by 2050-70 requires a range of approaches and technologies including electrification, the use of low-carbon hydrogen, sustainable biofuels and carbon capture, utilisation and storage (CCUS). Studies from organisations such as the IPCC and IEA conclude that CCUS, with its versatility of application, demonstrated effectiveness and ability to deal with enormous volumes of emissions, is a necessary element of the technology suite that must be deployed. An increasing number of countries include CCUS in their long-term climate change mitigation policies.

CCUS has grown rapidly in the past few years, with new projects announced and in planning and construction. However, CCUS is still in the early stages of technology and market development.

DEVELOPMENTS IN CARBON CONVERSION TECHNOLOGIES

CO_2 is a valuable commodity and can be converted into a variety of value-added products including fuels, chemicals, polymers and building materials via multiple chemical and/or biological processes. Many technology pathways exist for carbon conversion, which are at varying levels of technical and commercial maturity.

CO_2 can be combined with hydrogen to synthesise hydrocarbon fuels that can replace many of the fossil-based fuels currently available. CO_2 can also be used to make chemical intermediates such as syngas and methanol as the basis of other chemicals. A host of technologies based on mature processes but with specifically designed catalysts for converting CO_2 to established commercial products have been developed. Several technologies have been implemented successfully and are now in commercial use; some innovative processes have been developed and reached the commercialisation stage; and many more being developed are at the pilot and laboratory stages.

Figure 1 Atmosfair FairFuel Power-to-Liquid kerosene plant (Image credit: dpa picture alliance / Alamy Stock Photo)

Commercial plants are operational today in Asia, America, Europe and the Middle East producing synthetic fuels, chemicals and/or polymers from CO_2 emitted from various sources. CO_2-to-Fuel projects have been announced, or are in development worldwide, using various technologies.

The market for building materials from the carbonation of industrial wastes with captured CO_2 and CO_2-cured concrete has developed rapidly in the past few years. A group of companies are supplying various carbonation and CO_2-curing products and technologies on the market and more companies are commercialising their novel processes. CO_2-curing processes have been adopted in concrete production facilities worldwide, and several plants for CO_2 mineralisation of wastes for commercial production of aggregates and other valuable products are in operation.

With continued technological development, it can be expected that carbon capture and use (CCU) will be increasingly found in commercial applications.

POTENTIAL CONTRIBUTION OF CCU TO ACHIEVING NZE GOAL

The climate change mitigation benefits of a CCU product depend on several factors including the scale of its application, the life-cycle emissions of the product that it displaces, and the source of energy used. Almost all the CCU pathways investigated exhibit potential for lower life cycle emissions per tonne of product compared to conventionally produced counterparts. Thus, CCU can contribute to emissions reduction where the application is scalable, uses low-emission energy, and

displaces a product with higher life-cycle emissions. In addition, CCU offers a versatile and practical solution for emissions reduction in hard-to-abate sectors where alternatives are technically limited.

The potential demand for CO_2 by different CCU products, estimated by the IEA, shows that CO_2-derived fuels have the greatest market potential with an annual demand for CO_2 of >5 Gt. Building materials and chemical intermediates can generate a CO_2 demand of between 1–5 Gt/y, and CO_2 demand from polymers is >1 Gt/y. There is interest in CO_2-derived synthetic fuels for aviation and shipping. For example, the EU has introduced new standards for the use of sustainable fuels, which could increase the uptake of CCU for the production of CO_2-derived fuels in the region.

The growth in demand for CO_2 is limited to the anticipated market size of the CCU products. Due to many uncertainties, the estimated global CO_2 demand from CCU is wide ranging, from 1 $GtCO_2$/y to 7 $GtCO_2$/y in 2030. The higher figure of 7 $GtCO_2$/y equates to nearly 20% of current global CO_2 emissions, which is significant but not adequate for climate change mitigation. Thus, CCU can have a role in complementing other mitigation measures and contribute as part of an 'all technologies' approach to meeting global energy and climate goals.

In addition, CCU can generate useful income to offset carbon removal costs, providing a low-cost decarbonisation solution in some sectors and regions. It also provides a new source of essential carbon feedstock in the transition from fossil fuel resources, and so helps to close the carbon loop and create a circular economy. Therefore, CCU can be used as a supplement to other technologies and measures and can play an important role in efforts to achieve NZE and a circular economy.

1 INTRODUCTION

A clean energy transition towards net zero emissions (NZE) requires fundamental changes in the way energy is produced and used. Achieving NZE requires diverse approaches from different sectors and a broad suite of technologies including electrification, hydrogen, sustainable biofuels and carbon capture, utilisation and storage (CCUS). CCUS comprises a group of technologies covering CO_2 capture, processing, transport, conversion and storage. Modelling of pathways to NZE by several organisations, including the Intergovernmental Panel on Climate Change (IPCC) and the International Energy Agency (IEA), indicates that CCUS, with its versatility of application, demonstrated effectiveness and ability to deal with enormous volumes of emissions, is a necessary element of the technology suite that must be deployed.

The IEA (2020) found that CCUS can contribute to a clean energy transition in several ways:

- *reducing emissions from existing facilities*: retrofitting CCUS to existing power and industrial plants could cut CO_2 emissions by 600 Gt over the next five decades – almost 17 years' worth of current annual emissions;
- *a solution for some of the most challenging emissions*: for heavy industries that account for nearly 20% of global CO_2 emissions, CCUS is practically the only technology solution for processes such as cement production, and it is the most cost-effective approach to decarbonise other processes such as iron and steel and chemicals manufacturing (Kelsall, 2023);
- *a cost-effective pathway for low-emission hydrogen production*: CCUS can allow economic production of low-carbon hydrogen which has a vital role to play in decarbonising hard-to-abate sectors such as transport, industry and buildings, and hence, supporting a rapid scaling-up of low-emission hydrogen production to meet current and future demand from new applications (Zhu, 2023);
- *removing CO_2 from the atmosphere*: CCUS is important for removing carbon from the atmosphere to offset emissions that cannot be avoided or reduced directly; a crucial part of NZE goals.

The IEA (2020) concludes that:

> 'REACHING NET ZERO WILL BE VIRTUALLY IMPOSSIBLE WITHOUT CCUS', AND 'MOVING THE NET ZERO GOALPOSTS FROM 2070 TO 2050 WOULD REQUIRE ALMOST 50% MORE CCUS DEPLOYMENT'.

In addition to reducing emissions, carbon dioxide utilisation technologies enable carbon cycling by converting captured CO_2 into value-added commercial products such as fuels, chemicals, polymers and building materials. Through the substitution of fossil fuel-based raw materials with captured CO_2

and increased use of renewable energy, the integration of CCU-based manufacturing can contribute to a low-carbon economy. The opportunities for CCU are vast, with potential applications spanning various sectors from gas and liquid natural gas processing, production of hydrogen, chemicals and synthetic fuels, renewable energy integration, power generation and distribution, and more. Therefore, CCU can create a demand for captured CO_2 as a feedstock and the income from selling it could partially offset the cost of carbon capture until carbon prices are sufficiently high.

Fossil fuel-based power plants for electricity generation are employed on an enormous scale worldwide. In most OECD countries their use is declining, but in China, India and some other countries, coal-fired power plants remain a central or even growing part of electricity systems. In regions without access to good renewable resources or low-cost natural gas, ending local coal production and consumption may not be economically or politically feasible. In these cases, CCUS will be essential to reduce carbon emissions, enhance energy security, and support what has been called a just transition to a low-carbon economy.

CCUS is central to the least-cost pathways to NZE. Renewable energy is not always a feasible or low-cost option for decarbonisation. Although the use of renewable energy is expanding it may not be economically (or politically) viable to prematurely retire new and efficient coal power plants, particularly in Asia. There can be a role for CCUS to decarbonise the dispatchable power plants required to support intermittent wind and solar power and for the decarbonisation of newly built fossil power plants. The IPCC (2022) highlighted CCUS as an essential part of achieving NZE in the energy sector by 2050. The report warns that without CCUS, the world's fleet of coal and gas plants would need to retire 23 and 17 years early, respectively, to keep emissions low enough to attain the Paris Agreement climate targets. It suggests that by adopting CCUS technologies, carbon-intensive facilities could avoid becoming 'stranded assets' prematurely which would increase transition costs and reduce public acceptance.

CCUS can enable the energy sector to move towards NZE in a realistic and cost-effective way, whilst meeting the UN Sustainable Development Goals (SDGs):

- Universal access to affordable, reliable, sustainable and modern energy (SDG 7);
- Building resilient infrastructure, promoting inclusive and sustainable industrialisation and fostering innovation (SDG 9);
- Circular economy and resources efficiency through sustainable production and consumption (SDG 12); and
- Combating climate change and its impacts (SDG 13).

CO_2 can be used as an alternative carbon source to fossil carbon and be converted into a wide range of value-added products. CO_2 is already widely used as a direct input for products such as carbonated beverages, fire extinguishers, and cooling agents, as well as for enhanced oil recovery (EOR). CO_2 can also be chemically or biologically transformed into commercially established products such as

synthetic fuels, chemicals and polymers, and building materials. CO_2 conversion technologies are attracting increasing interest from governments, industry and investors for their potential role in carbon emissions mitigation and in a circular NZE economy. There has been great momentum behind CCUS in 2022, with projects, policies, and funding announced globally in America, Asia-Pacific, Europe and the Middle East. Extensive research and development (R&D) is being carried out to improve existing systems and develop better, innovative CCU technologies.

This report reviews the latest developments in CCUS with a focus on CCU technologies. It updates the ICSC report '*Developments in CO_2 utilisation technologies*' (Zhu 2018). In Chapter 2 there is an overview of recent developments in policies and regulations on CCUS in various countries and regions. Chapter 3 provides a brief review of the technologies for CO_2 capture and conversion (utilisation), and the current status of CCUS. Chapter 4 describes recent developments in CCU technologies and applications with a focus on technologies that are emerging in the commercial market or are close to being commercialised. Chapter 5 assesses the potential market for CO_2-derived products and their competitiveness with conventionally produced counterparts. The climate change mitigation potential and the role of CCU in achieving NZE and in a circular economy, as well as drivers and barriers to CCU deployment, are also discussed. The conclusions are drawn in Chapter 6.

2 POLICY, LEGAL AND REGULATORY FRAMEWORKS

The IPCC (2022) report highlighted the need for CCS, demonstrating its effectiveness and viability across various pathways to NZE. In the IPCC-modelled pathways, 5–16 $GtCO_2/y$ needs to be captured and stored at the point of reaching NZE. In the IEA Net Zero Emissions by 2050 Scenario (the NZE Scenario), CCUS deployment needs to grow by a factor of almost 200 to capture over 7.6 $GtCO_2/y$ by 2050 (IEA, 2021). The successful global deployment of CCUS at this scale will depend on the establishment of robust legal and regulatory frameworks that provide effective stewardship and oversight of CCUS activities. Supporting policies that incentivise payment of the high costs of CCUS and de-risk investing in it are also vital to promote capacity building. Several countries have developed comprehensive legal and regulatory frameworks for CCUS. This chapter provides an overview of the recent developments of policies and regulations on CCUS.

2.1 A GLOBAL LANDSCAPE

For several decades, international organisations such as the United Nations (UN) have been raising awareness of climate change and the depletion of resources. The Kyoto Protocol, signed in 1997 by 192 parties, ran from 2005 to 2020, was the first international treaty implemented under the UN Framework Convention on Climate Change (UNFCCC) that committed state parties to reduce greenhouse gas (GHG) emissions. The Kyoto Protocol was superseded by the 2015 Paris Agreement, which entered into force in 2016. The Paris Agreement is a legally binding international treaty signed by 193 states plus the European Union (EU). The Agreement sets long-term goals to guide all nations (UN, nd):

- substantially reduce global GHG emissions to limit the global temperature increase in this century to 2°C while pursuing efforts to limit the increase even further to 1.5°C;
- review countries' commitments every five years;
- provide financing to developing countries to mitigate climate change, strengthen resilience and enhance abilities to adapt to climate impacts.

At the heart of achieving the objectives of the Paris Agreement are the Nationally Determined Contributions (NDCs). In their NDCs, countries communicate actions they will take to reduce their GHG emissions in order to reach the goals of the Paris Agreement. Every five years, each country is expected to submit an updated NDC. An increasing number of countries are including CCUS in their NDCs (*see* Figure 1).

Figure 1 Countries' NDCs that include CCUS (GCCSI, 2022a)

Accounting for nearly 80% of global CO_2 emissions, the G20 member states have a major role to play in collective actions to address climate change. Accordingly, the G20 members have addressed climate change in some capacity at every summit held since the inaugural one in 2008 (Dawe and others, 2021). In the G20 Hamburg Climate and Energy Action Plan for Growth published at the 2017 G20 Summit, energy ministers encouraged countries that opt to use CCUS to continue to undertake research, development and deployment (RD&D) and to collaborate on large-scale demonstration projects (MOFA, 2017). Since then, there has been an increasing recognition by governments of the critical role of CCUS. In recognition of the key importance and ambition of reducing emissions, taking into account system efficiency and national circumstances, a circular carbon economy (CCE) platform was developed during the 2020 G20 Summit and endorsed by the G20 leaders with its 4Rs framework (Reduce, Reuse, Recycle and Remove) (Dawe and others, 2021). In the 2021 G20 summit, the leaders recognised the need for investment and financing for advanced and clean technologies, including CCUS or carbon recycling to abate emissions, considering that fossil fuels retain a vital role in the energy mix (G20, 2021). At the 2022 G20 summit, the leaders determined to accelerate the implementation of NDCs and the sustainable transition towards low GHG emissions through carbon recycling (G20, 2022).

The global policy, legal and regulatory development for CCUS remains dynamic. Several countries have developed comprehensive legal and regulatory frameworks for CCUS, which are detailed in the IEA database of laws and regulations that support a framework for CCUS development (IEA, 2022a).

A brief review of the regional and national legal and regulatory framework and policies on CCUS is provided in the following section.

2.2 REGIONAL POLICY AND REGULATORY DEVELOPMENT

2.2.1 North America

Canada has pledged a 40–45% reduction in emissions from 2005 levels by 2030 and set a legally binding target of NZE by 2050. In early 2022, the Canadian government released its 2030 Emissions Reduction Plan aiming to position its industries as sustainable and competitive. Following this publication, Canada issued its 2022 federal budget which supports CCUS via an investment tax credit. The tax credit rate is 60% for direct air capture (DAC) projects, 50% for all other carbon capture projects, and 37.5% for transport, storage, and use from 2022 to 2030. From 2031 to 2040, the tax rates drops to 30%, 25%, and 18.75%, respectively. From January 2022, the tax credit can be claimed by businesses that incur eligible expenses related to purchasing and installing equipment used in a suitable new project that captures CO_2. Companies can only claim the tax credit if they agree to abide by a validation and verification process, prove that the project meets CO_2 storage requirements, and produce a climate-related financial disclosure report (GCCSI, 2022a).

Canada's carbon tax and an upcoming clean fuel standard are also expected to play a role in incentivising CCUS. Every province in Canada either has its own carbon pricing system or is covered by a federal backstop which consists of a fuel charge on its production and distribution and a cap-and-trade system for industrial emissions. The Clean Fuel Standard, to be implemented in 2023, creates a cap-and-trade system to encourage decreasing the lifecycle carbon intensity of fuels sold in Canada. The required rate of carbon intensity reduction will be increased over time. One way for companies to generate credits under this programme will be to capture and store the CO_2 emitted from their operations (Tsafos and Naimoli, 2022).

Recognising the contribution that CCUS can make to reducing emissions and meeting its climate goals, the government is developing a Carbon Management Strategy (formerly known as the CCUS Strategy) to incentivise the development and adoption of CCUS technology (NRCan, 2023). An early draft of the forthcoming strategy seeks to store 15 $MtCO_2/y$ by 2030 (Tsafos and Naimoli, 2022). CCUS is also likely to play a role in the country's hydrogen production, which the government wants to meet 30% of energy consumption by 2050.

The Canadian government has provided significant funding for RD&D of CCUS technologies. The Net Zero Accelerator Initiative is a CA$8 billion (US$6.2 billion) fund announced in 2020 that would invest in projects to help decarbonise large emitters. The Canadian 2021 budget allocated CA$319 million (US$248 million) for CCUS R&D over five years. In addition, alongside the government of British Columbia and the Canadian division of Royal Dutch Shell, the federal government granted CA$35

million (US$27 million) in 2021 to help fund the Centre for Innovation and Clean Energy. The Centre will undertake R&D projects in technologies including CCUS (Tsafos and Naimoli, 2022).

The fossil fuel-producing provinces, Alberta and Saskatchewan, have taken initiatives with their own CCUS priorities. Alberta's strategy relies on providing funds to developers and is preparing to encourage the development of CCUS hubs (Tsafos and Naimoli, 2022). In 2013, Alberta passed the Carbon Capture and Storage Funding Act, allowing the province to invest up to CA$2 billion (US$1.6 billion) in CCUS projects. The Alberta Hydrogen Roadmap was also announced in 2021, which outlines Alberta's intention to become an international leader in clean hydrogen (GCCSI, 2022a). CCUS is a key part of the roadmap. On 1 January 2023, amendments to Alberta's Technology, Innovation and Emissions Reduction Regulation (TIER) came into effect. The amended TIER increases the carbon credits in Alberta to levels aligned with the federal Greenhouse Gas Pollution Pricing Act. The amendments also establish a new set of TIER credits designed to facilitate TIER participation by CCS proponents including new CCS credits (comprising sequestration credits and capture recognition tonnes), accelerated credit expiry, and increased credit use limit (Harper and Bakker, 2023).

In September 2021, the Saskatchewan government pledged to make some key policy changes for economic support for projects and regulatory changes to reduce costs for the industry:

- extend a 20% investment tax credit for CO_2 pipeline infrastructure;
- review royalties for EOR projects;
- update regulations for CO_2 use and storage;
- explore opportunities for CCUS hubs in the province; and
- identify a new way to credit CCUS projects for emissions reductions.

In November 2021, the government of Saskatchewan announced the eligibility of pipelines transporting CO_2 (for CCUS including EOR) for the provincial Oil Infrastructure Investment Program (Saskatchewan, 2021).

In the **USA** CCUS is seen as essential in meeting the goals of 100% clean electricity by 2035 and NZE by 2050. The US policy support for CCS RD&D began in 1997, and a CCS RD&D Roadmap was created by the US Department of Energy (DOE) in 2005 (Bright, 2021). In 2008, the government introduced Section 45Q which provides a tax credit to incentivise the deployment of CCUS. In 2020, the Utilizing Significant Emissions with Innovative Technologies (USE IT) Act was signed into law, which extends the 45Q tax credit for CCUS for two years and supports carbon utilisation and DAC research. Specifically, the USE IT Act clarifies that CCUS projects and CO_2 pipelines are eligible for streamlined permitting under the Fixing America's Surface Transportation (FAST) Act. The Act also directed the White House Council on Environmental Quality (CEQ) to create guidance to assist federal agencies with the regulation and permitting of CCUS activities in the USA, The guidance was issued in 2022 (CEQ, 2022).

The Energy Act of 2020 gave CCUS RD&D a significant boost as $6.72 billion in funding was authorised for CCUS spending between 2021 and 2025 including $2.6 billion for six commercial scale demonstration projects, $1 billion for large-scale pilot projects, $910 million for R&D, $800 million for carbon storage, and $283 million for a carbon utilisation programme (Bright, 2021).

In 2021, the US enacted the Infrastructure Investment and Jobs Act (IIJA), which included over $12 billion to be spent on CCS over the next five years. The legislation includes funding for CCUS RD&D, CO_2 transport and storage infrastructure, carbon utilisation market development, four regional DAC with carbon storage hubs, and a DAC Technology Competition (GCCSI, 2022a).

Also in 2021, the US introduced the SCALE Act (Storing CO_2 and Lowering Emissions Act) aiming to drive the build-out of critical CO_2 transport and storage infrastructure and support the development of CCUS and CO_2 removal technologies. The SCALE Act provides federal support for CO_2 transport and storage infrastructure within the USA, offers economic opportunities and creates employment.

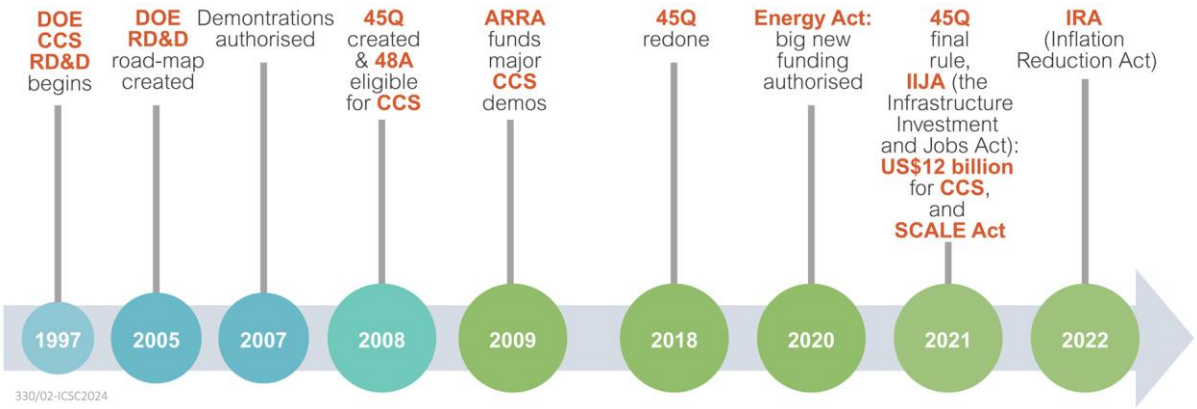

Figure 2 A brief history of CCUS policies enacted in the USA (Modified from Bright, 2021)

In 2022, the US introduced a significant stimulus for CCUS investment through the Inflation Reduction Act (IRA), to expand and extend the 45Q tax credit (CATF, 2022). The changes to 45Q provide up to 85 $/t for CO_2 permanently stored and 60 $/t for CO_2 used, provided emissions reductions can be clearly demonstrated. The credit amount significantly increases for DAC projects to 180 $/t for CO_2 permanently stored and 130 $/t for CO_2 utilised. The IRA broadens the definition of qualified facilities and has made the tax credit more accessible to a broad array of investors and developers. The IRA extended the commence-construction window by seven years (to 1 January 2033) for qualifying projects and includes funding for CCUS projects. The ruling included important clarifications about geological storage certification, aggregation of multiple projects, and a broader definition of carbon utilisation. Figure 2 illustrates the brief history of the CCUS policies enacted in the USA.

In addition, the US Environmental Protection Agency (EPA) is developing proposed rule revisions to improve transparency on CCUS activities, the DOE is committing $5 million for university training and research related to carbon management, and the Federal Permitting Improvement Steering

Council is facilitating a collaborative CCUS project review among its member agencies (Bachtel and others, 2022).

Several states including Indiana, West Virginia, and Wyoming have enacted or are progressing with legislation and policies on CCUS RD&D. The reliable and dispatchable low-carbon energy standards (HB0200) enacted in Wyoming in 2020 promote the transition to clean energy through retrofitting existing fossil fuel power plants with CCS by allowing cost recovery of investment in CCS from ratepayers and also helps to stimulate investment (State of Wyoming, nd). The California Air Resources Board released its Draft Scoping Plan in 2022. The Plan presents a path for carbon neutrality by 2045 and calls for the deployment of CCS technology in sectors where non-combustion options are not technically or economically viable for meeting 2045 goals (GCCSI, 2022a).

2.2.2 Asia-Pacific

Australia is committed to reaching NZE by 2050 and views CCUS as key to emissions reduction. The legal framework for promoting and regulating CCUS in Australia is divided among the federal government, the states and territories (Power, 2021; GCCSI, 2022b). Federal CCS laws only apply to the offshore areas within the Commonwealth jurisdiction, while state and territory CCS laws apply to onshore and offshore projects within their jurisdictions. However, CCS investment policy can come from both federal and state or territory governments. The federal legislation provides a framework for licensing, regulatory oversight, and applicable environmental standards for CCS projects in Commonwealth waters. The principal piece of legislation that regulates CCS projects in Commonwealth waters is the 2006 Offshore Petroleum and Greenhouse Gas Storage Act (Rogers and others, 2022). The 1999 Environment Protection and Biodiversity Conservation (EPBC) Act (Cth) is also relevant to CCS activities, regardless of whether they fall within Commonwealth or state and territory jurisdiction. EPBC Act approval is required where CCS projects concern matters of national environmental significance.

In 2020, the federal government published its First Low Emissions Technology Statement, a proposed GHG emissions reduction strategy that gives CCS a prominent role (Power, 2021). The Statement emphasises the importance of CCS in sequestering GHG emissions and commits the government to provide AU$50 ($37.6) million in R&D and for the amending of legislation to ensure CCS is eligible for government support. The Australian government further announced AU$263.7 million in new funding to support CCS and/or CCU projects and hubs and AU$275.5 million to support four clean hydrogen hubs (GCCSI, 2021).

In late 2021, a CCS methodology was included under the Emissions Reduction Fund which incentivises CCS projects in Australia. This is the first financial incentive scheme for CCS-specific CO_2 abatement in the Asia-Pacific region and may be significant in the widescale deployment of projects. In 2021, Australia published a CO_2 Utilisation Roadmap that explores the risks and opportunities associated with the scale-up of CCU and identifies four opportunity areas for Australia to pursue: direct use of

CO_2, mineral carbonation, conversion of CO_2 to create chemicals and fuels, and biological conversion of CO_2 (CSIRO, 2021). The Australian government has provided significant grant funding and policy support for RD&D of CCUS infrastructure.

There is significant variation across states and territories; the relevant frameworks are comprehensive in some parts of the country but much less so in other parts. Legislation for CCS projects has been in place in Victoria and Queensland for over a decade, while Tasmania, New South Wales and the Northern Territory do not have specific legislation that governs CCS projects (Rogers and others, 2022; Power, 2021). The Western Australian Government is currently (October 2023) drafting a Greenhouse Gas Storage and Transport Bill which will underpin the regulatory regime for CCS in the state.

China has pledged to achieve peak carbon emissions before 2030 and carbon neutrality by 2060. China has identified CCUS as a key technology and included it as one of the GHG mitigation technologies in its NDC. The National Climate Change Mitigation Plan issued in 2007 emphasised the importance of CCUS in reducing carbon emissions (Song and others, 2022). Also in 2007, China's Special Scientific and Technological Action Plan on Climate Change regarded CCUS as a key carbon-reduction strategy and promoted CCUS R&D and demonstration projects. China has expanded existing environmental regulations to include CCUS projects and clarified the CCUS approval process. In 2011, China introduced its first Roadmap for Carbon Capture, Utilisation, and Storage Technology in China, which was updated in 2019 (Li and others, 2014; ADB, 2022). The Roadmap outlines technical, legal, policy, financial and public engagement solutions that need to be implemented to move CCS from early demonstration projects to full-scale commercialisation. Since the publication of the 12th Five-Year Plan (FYP) (2011-2015) CCUS has been included in every subsequent FYP. In 2021, China published the Action Plan for Carbon Dioxide Peaking Before 2030 (1+N) which lays some of the groundwork for CCUS policy directions (NDRC, 2021). In total, China has issued over 50 CCUS-related policies involving various ministries (Wu, 2022). These policies support CCUS by encouraging its application in hard-to-abate sectors and emission-intensive areas, unlocking financial support through market mechanisms, conducting research on storage resources, and promoting standards development and technology research. In addition, around 300 provincial government institutions (most of the provinces have energy- and emissions-intense industries as major economic pillars) have published CCUS-related development strategies, showing a recognition of the importance of CCUS. However, despite progress and some policy documents outlining a role for CCUS, issues such as the lack of a policy-based, sustainable business model for CCUS and insufficient incentives remain challenges for CCUS deployment in China.

Japan has committed to achieving NZE by 2050 and sees CCUS as key to meeting the goal. In 2019, the Ministry of Economy, Trade and Industry (METI) released the Roadmap for Carbon Recycling Technologies to specify goals, technological challenges and timeframes regarding carbon recycling technologies and to accelerate innovation. The Roadmap was revised in 2021 to align with Japan's 2050

carbon neutrality goal. The updated roadmap adds new technological areas such as DAC and synthetic fuels, brings forward the beginning of the widespread adoption of (general purpose) carbon recycling products to around 2040 and enhances international cooperation (METI, 2021). In January 2023, METI set an annual target of a CO_2 storage capacity of 6–12 Mt by 2030 under a long-term roadmap for CCS (Obayashi, 2023). METI estimates that Japan will be able to store 120–240 $MtCO_2/y$ in 2050. To achieve this goal, Japan will aim to significantly reduce CO_2 separation and recovery costs. METI also wants legislative frameworks in place to allow companies to launch full-scale CCS operations from 2030. With limited storage potential, Japan has been investigating the possibility of transporting and storing its CO_2 to other nations. The Japanese government also promotes bilateral and multilateral CCUS collaborations. For example, in June 2021, Japan launched the Asia CCUS Network to support capacity development and promote knowledge sharing (GCCSI, 2021).

South Korea has pledged to achieve carbon neutrality by 2050 and considers CCUS an essential tool to achieve its climate goals. Specifically, South Korea aims to reduce CO_2 emissions by 11.2 Mt/y through CCUS by 2030 (Doneva, 2023). South Korea published a Five-Year Green Growth Plan in 2009 and Ten Core Green Technologies in 2010 which included CCS (Jung and others, 2022). In addition, the government established the National CCS Comprehensive Plan in 2010 to deal with CCS directly (Park, 2018). The investment in CCS R&D increased nearly three times between 2008 and 2012 to around 74.2 billion South Korean Won ($56 million) (Jung and others, 2022). In June 2011, the Korea CCS 2020 Basic Plan was published, and significant funding was made available to support large-scale CCS demonstration and commercialisation projects. In 2016, Korea released the 'National Strategic Project Demonstration Roadmap for Carbon Resourceization' which expanded the nine major national strategic projects to include CCU. Thus, Korean policies from the 2050 Carbon Neutrality Strategy to the 2050 Carbon-Neutral Scenario all consider CCUS as an important technology to reduce CO_2 and meet NZE goals. In particular, the CCU Technology Innovation Roadmap introduced in 2021 set milestones to 2050 for key technologies in five major areas including CO_2 capture, chemical conversion, biological conversion, mineral carbonisation, and other forms of carbon utilisation. However, the lack of laws pertinent to CCUS remains a hurdle to deployment due to uncertainties in the implementation of CCUS in South Korea.

Elsewhere in Asia, **India** aims to achieve NZE by 2070 and is an active participant in the Carbon Capture Innovation Challenge under Mission Innovation, an international platform launched in 2018 for co-ordinating and collaborating on CCUS R&D (Goldar and Dasgupta, 2022). In 2022, the Ministry of Petroleum and Natural Gas of India (MoPNG) issued a Draft 2030 Roadmap for Carbon Capture Utilization and Storage (CCUS) for Upstream E&P Companies which provides the direction and guidelines necessary for the development and implementation of CCUS techniques in the Indian oil and gas sector (MoPNG, 2022).

Indonesia is a proponent of CCS and a frontrunner in its deployment in Southeast Asia with a broad vision for delivering project-level abatement using CCS (GCCSI, 2022a). Indonesia is also developing

the opportunity for the country to become a storage facility for the region. The Government is progressing with policy and regulatory development as foreign oil and gas operators drive projects. A task force, coordinated by the Ministry of Energy and Mineral Resources, was established in 2021 to draft CCUS regulations. However, both India and Indonesia are yet to establish CCUS regulatory frameworks and supporting policies to encourage CCUS deployment in the country.

2.2.3 Europe and the UK

The **EU** adopted the CCS Directive (Directive 2009/29/EC) in 2009 which identifies CCS as a bridging technology for achieving its climate goals and provides a legal framework for the safe geological storage of CO_2 (EC, nda). CCU technology is regulated in Directive (EU) 2018/2001 which promotes the use of renewable energy and renewable fuels of non-biological origin including those produced from captured CO_2 (EC, ndb). The European Green Deal, approved in 2020, is a set of policy initiatives from the European Commission (EC) which aim to make the EU climate-neutral in 2050 and includes a host of measures to achieve it. In December 2021, the EC published a Communication on Sustainable Carbon Cycles (COM/2021/800) that sets the long-term objective to restore sustainable and climate-resilient carbon cycles. It lists key actions to support industrial CCUS, including the assessment of cross-border CO_2 infrastructure deployment needs at EU, regional and national levels until 2030 and beyond (EC, nda). Besides the proposal for a revised Renewable Energy Directive which encourages fuels produced by CCU, the Commission has also proposed the ReFuelEU Aviation Initiative that will oblige fuel suppliers to blend increasing levels of sustainable aviation fuels (SAF) in jet fuel including synthetic low carbon fuels, known as e-fuels. Furthermore, the Strategic Energy Technology (SET) Plan TWG9 identifies research and innovation priorities for CCS and CCU. The EC has also approved several key pieces of legislation as part of the 'Fit for 55' package released in late 2021 that aims to reduce GHG emissions in the EU by at least 55% by 2030 (ECF, 2022). The key elements contain legislation relevant to CCS deployment, including the EU Emissions Trading Scheme (ETS) law and the Carbon Border Adjustment Mechanism (CBAM).

The EU actively supports CCUS RD&D. The Innovation Fund will provide around €10 billion over 2020-30 for the commercial demonstration of innovative low-carbon technologies (CLERENS, nd). The fund is open to any EU country, Iceland and Norway and projects including CCS and CCU technology can apply. The EU launched a key funding programme, Horizon 2020, for research and innovation with nearly €80 billion available over seven years from 2014 to 2020. The programme has been succeeded by Horizon Europe which runs until 2027 and has a budget of €95.5 billion (EC, ndc). The funding programme is the EU's Scientific Research Initiative to support the creation and better dissemination of the knowledge and technologies including that of CCUS. The EC also enables EU countries to support CCUS technology through state aid under certain conditions specified in its Guidelines on State Aid for Climate, Environmental Protection and Energy 2022 (EC, ndb).

The **UK** government announced its new approach to CCUS in the Clean Growth Strategy of 2017 (GOV.UK, 2019). The approach is designed to enable the UK to become a global technology leader for CCUS and ensure that the government has the option of deploying CCUS at scale during the 2030s, subject to costs coming down sufficiently. The government has set out action under three themes:

- re-affirming its commitment to deploying CCUS in the UK subject to cost reduction;
- international collaboration on CCUS; and
- CCUS innovation.

The CCUS Cost Challenge Taskforce has been established to provide advice on the steps needed to reduce the cost of deploying CCUS in the UK. Following its advice, the government published the *UK CCUS Deployment Pathway: An Action Plan* outlining the targets for addressing policy impediments and establishing market mechanisms for CCUS.

In 2021, the UK government released the Net Zero Strategy which sets out policies and proposals for decarbonising all sectors of the UK economy to meet its net zero target by 2050. It includes carbon removal deployment goals and two new RD&D programmes focused on demonstration. The government has been working on initiatives to develop CCUS industrial decarbonisation clusters. *The Carbon Capture, Usage and Storage Net Zero Investment Roadmap*, published in April 2023, outlines joint government and industry commitments for the deployment of CCUS in the UK and sets out its approach to delivering four CCUS low carbon industrial clusters, capturing 20–30 $MtCO_2/y$ across the economy by 2030 (GOV.UK, 2023a).

The UK has invested in RD&D on a wide range of GHG removal technologies, primarily for CO_2. The first GHG removal RD&D programme ran from 2017 to 2021 and funded 11 projects totalling £8.6 million ($9.7 million) (Smith and others, 2023). In one of the two RD&D programmes under the Net Zero Strategy, a total of £5.9 million ($6.7 million) has been provided in Phase One to fund 23 pre-commercial innovation projects focusing on the design and feasibility of CCUS technology. In Phase Two (ending March 2025), an additional £58 million ($65 million) will be awarded to pilot the 15 most promising designs. In 2020, the Government published *The Ten Point Plan for A Green Industrial Revolution* which is to mobilise £12 billion of government investment and more from the private sector in ten areas including CCUS (GOV.UK, 2020). In the 2023 Spring Budget, the government committed to invest £20 billion over a period of 20 years to scale up CCUS projects across the UK (GOV.UK, 2023b).

2.2.4 Middle East and North Africa

Many countries in the Middle East and North Africa (MENA) region have pledged to achieve NZE by 2050-60 and have introduced climate change mitigation policies, but CCUS-specific policies are rare (GCCSI, 2022a). CCUS development in the Middle East could be driven mostly by the value of EOR, low-emission hydrogen production and the potential of the region as a hub for CCUS and carbon

trading. Hence, CCUS deployment in the region is less dependent on policy incentives than in other parts of the world. The MENA governments are focusing on the environmental impact and strategic growth of decarbonisation technologies rather than on policy development. Egypt, Saudi Arabia and the United Arab Emirates (UAE) have announced the establishment of voluntary carbon market initiatives and fully regulated carbon trading exchange and trading schemes, which will drive the carbon market in the region, benefiting all decarbonisation technologies including CCUS.

Many African countries face the challenges of balancing economic growth and increased access to energy for millions of people with decarbonisation. Progress in CCUS development has been slow in the region. However, the production of clean hydrogen and other low-carbon fuels using renewable energy could be part of the CCUS growth story with some hydrogen projects in development, particularly in North Africa.

2.3 COMMENTS

As the global response to climate change has advanced, most governments have announced or are considering their NZE strategies. An increasing number of countries rely on CCUS technologies in their long-term climate change mitigation policies. Several countries have developed comprehensive legal and regulatory frameworks for CCUS. North America and Europe lead the way hosting the most robust climate and CCUS policy mechanisms, while policy is also advancing in the Asia-Pacific. However, regulations and policies on climate and/or CCUS are underdeveloped in other countries.

Governments have an important role in supporting CCUS investment. There is a need for national governments to establish legislation and regulatory frameworks to enable and encourage more CCUS activity. A range of frameworks can be adopted to help the uptake of CCUS and its rapid scale-up. For example, national governments can provide financial support such as capital grants and tax credits to reduce the costs of commercial CCUS projects, and incentives should be distributed across the value chain. Clear decarbonisation targets and roadmaps for implementing CCUS should be established setting the technical, legal, policy, financial and public engagement pathways. National governments should also participate in infrastructure developments to catalyse CCUS investments. Robust frameworks and supportive policies for CCUS could boost economic growth. Internationally, there is a need to strengthen policy cohesion and enhance market confidence to encourage CCUS investment and deployment. Strategic partnerships and collaboration among governments and private sectors in different countries are required to drive deployment, particularly through CCUS networks.

3 THE STATUS OF CCUS

CCUS is a broad term covering a wide range of technologies including CO_2 capture, processing (purification, compression, and liquefaction), transport, conversion and storage. Some of the technologies have been in commercial operation for decades. However, the processes are generally energy-intensive and expensive. Extensive R&D is ongoing to improve the existing technologies, lower their cost, and develop better innovative ones. Despite the current high cost, CCUS is attracting increasing interest from governments, industries and investors. This chapter provides a brief review of the technologies for CO_2 capture and conversion (utilisation) and the status of CCUS.

3.1 CCU TECHNOLOGIES

3.1.1 Technologies for carbon capture

Carbon capture technologies can be divided into four categories:

- post-combustion carbon capture which separates CO_2 from the flue gas after the fuel is burnt;
- pre-combustion carbon capture which converts the fuel (by gasification) into a syngas consisting of hydrogen and CO_2. Once the CO_2 is separated, the remaining hydrogen-rich mixture can be used as fuel or feedstock;
- oxycombustion which involves burning a fuel in pure oxygen to produce a stream of CO_2, ready for sequestration; and
- direct air capture (DAC) that extracts CO_2 directly from the atmosphere.

There are several processes for post- and pre-combustion CO_2 capture including solvent-based chemical and physical absorption, solid sorbent-based chemical and physical adsorption, and membrane separation. The most advanced and widely adopted capture technologies are chemical absorption and physical separation. Many of the well-developed chemical absorption technologies are based on amine solvents. Absorption processes based on amine scrubbing have been developed and deployed commercially for decades for industrial processes such as natural gas processing, hydrogen production and other gas purification purposes. CO_2 capture rates of over 90% and in some cases up to 100%, can be achieved by existing technologies. Today, a variety of amine-based systems are commercially available from some of the world's most prominent technology providers such as Aker Carbon Capture, Mitsubishi Heavy Industries (MHI), and Shell. Descriptions of the state-of-the-art carbon capture processes from different suppliers are available elsewhere (GCCSI, 2022c).

Post-combustion CO_2 capture can be applied to conventional thermal power plants and many industrial processes such as cement, iron and steel making. However, separating CO_2 from the flue gas stream exiting these processes is challenging for several reasons:

- CO_2 is present at a dilute concentration (typically lower than 16% for coal power plants, for example, and less than 6% for gas power plants) and thus, a large volume of gas has to be treated;
- impurities such as particulate matter, sulphur dioxide (SO_2), and nitrogen oxides (NOx) in the flue gas can degrade sorbents and reduce the effectiveness of certain CO_2 capture processes;
- CO_2 is captured at low pressure (slightly above atmospheric). Compressing it from atmospheric to pipeline pressure will incur significant energy consumption or, for a power plant, a large auxiliary power load on the overall power plant system.

Consequently, the use of post-combustion CO_2 capture on power plants, cement and steel making, and other hard-to-abate industrial processes is limited. As discussed in Section 3.2.2, in addition to the commercial CCUS facilities operating around the world, there are CCUS pilot or demonstration projects as well as commercial projects in varying stages of development to add carbon capture plant to hard-to-abate industrial processes. The amine-based solvent absorption capture process has been successfully demonstrated on coal-fired power plants (see Section 3.2.3). There are also plans to install CO_2 capture systems in natural gas power plants.

Innovation in solvent scrubbing technology has been an active area of research. Amine solvent chemistry can be changed by using different amines, through the addition of additives or by a combination of both techniques (Menmuir and others, 2022). Improvements in optimising amine solvents and process design for CO_2 capture have been made and more are anticipated. Progress has also been made in developing innovative liquid absorbents such as ionic liquids and encapsulated absorbents, but these are still at an early stage of development.

Solvent scrubbing that separates CO_2 by physical absorption can have cost advantages over chemical solvent scrubbing due to its lower energy consumption and simpler process. Physical solvent scrubbing is often used to remove acid gas from natural gas and synthesis gas streams at high pressures. Many physical solvent systems are successfully operating in industry. In 2019, tests of pre-combustion CO_2 capture using a physical solvent process began at an integrated coal gasification combined cycle (IGCC) power plant in Japan. The demonstration has been successful with carbon capture performance exceeding targets including achieving a CO_2 capture rate of above 90% (Misawa, 2021).

Adsorption processes using solid sorbents require less energy and could provide economic advantages over solvent absorption processes. Materials such as activated carbonaceous materials, polymeric materials, zeolites, silica, metal-organic frameworks, and alkali-metal carbonates are being investigated as potential sorbents in pressure- or temperature-swing adsorption, and hybrid adsorption systems for CO_2 capture (Menmuir and others, 2022; IEAGHG, 2019).

Membranes perform as a filter resulting in the separation of gas mixtures. Based on their physical and chemical properties, there is a wide variety of membrane types applicable; for example, for the separation of hydrogen and CO_2 for pre-combustion capture, for CO_2 and nitrogen separation for post-combustion capture and oxygen and nitrogen separation (air separation) for oxycombustion. Membranes have been widely used in liquid separation such as micro- or ultra-filtration, reverse or forward osmosis, desalination and medical applications (Ji and Zhao, 2017). However, gas separation using membranes is still under development. Several types of membrane such as polymeric membranes, composite hollow fibre membranes, zeolite membranes, membrane contactors and mixed matrix membranes, have been developed and are being tested for CO_2 capture (Menmuir and others, 2022). Both solid sorbent adsorption and membrane separation technologies for carbon capture are under development with some tested at pilot scale.

Separately, a first-of-its-kind natural gas-fired power plant employing Allam Cycle technology has been successfully demonstrated at pilot scale, and a commercial 300 MWe gas power plant is to be built in Texas, USA, which is expected to be online in 2026 (NET Power, 2022). The Allam Cycle uses CO_2 as a working fluid in an oxyfuel supercritical CO_2 power cycle. Combustion of fuel produces a stream of CO_2 ready for sequestration. Development of a different version of the Allam Cycle for use with IGCC is ongoing.

In addition, other technology options such as enzyme-catalysed capture, cryogenic capture, chemical looping and oxycombustion are being investigated. A technoeconomic assessment of emerging CO_2 capture technologies for coal and gas-fired power plants is available (IEAGHG, 2019).

Two technological approaches are being commercialised for use in DAC: solid and liquid DAC. Solid DAC is based on solid adsorbents operating at ambient to low pressure (under a vacuum) and medium temperature of 80–120°C. Liquid DAC relies on an aqueous basic solution such as potassium hydroxide, which releases the captured CO_2 through a series of units operating at high temperatures, between 300–900°C (IEA, 2022b). As the concentration of CO_2 in the atmosphere is much lower (in ppm level) compared to the flue gas of a power plant, for example, DAC is more energy intensive and thereby, more expensive relative to other CO_2 capture technologies and applications.

Once the CO_2 is captured, it is compressed, usually into a liquid state, and transported by pipeline, ship, rail or road tanker. CO_2 can then be injected into, and permanently stored in deep geological formations. An alternative to permanent storage is to use the captured CO_2 as a feedstock for commercial products and services. The technological pathways for converting CO_2 into marketable products are described briefly in the next section and the recent advances are reviewed in the following chapters.

3.1.2 Technologies for carbon conversion

Carbon conversion covers a wide range of technologies and processes at varying levels of technical and commercial maturity. Technology pathways involved in the conversion of CO_2 to fuels, chemicals, polymers, and construction materials include catalytic, electrochemical, mineralisation, biological (using microbes and enzymes), photocatalytic and photosynthetic. Some technologies such as combining ammonia and CO_2 for urea (a fertiliser) production have been in operation at industrial scale for many decades. Others such as concrete curing using CO_2 and CO_2 mineralisation for making building materials, and the production of fuels and chemicals via electrochemical or bioconversion of CO_2 are emerging. Several companies such as CarbonCure, Carbon8, Solidia, Sunfire and LanzaTech are marketing their technologies (Zhu, 2018). There are several pilot demonstration and commercial projects, usually small in scale, already in operation and more projects are in development. Pathways for the production of CO_2-based fuels and chemicals such as electrochemical, photocatalytic, and thermocatalytic and electrocatalytic conversion, are highly energy-intensive and still in their infancy; they face commercial and regulatory challenges. Pathways such as reacting CO_2 with minerals or wastes such as iron slag to form carbonates for building materials are less energy-intensive and can be competitive with conventional methods. Early markets for CO_2 use in concrete manufacturing and building materials from waste and CO_2 are emerging.

Extensive R&D in carbon conversion technologies is being carried out. There is growing interest in, and support for, CCU from governments, industry and investors. Governments in countries including Canada, Japan, the UK, the USA and the EU are providing significant RD&D support for CO_2 use. The rapid developments in CCU RD&D in the past few years are reviewed in Chapter 4.

3.2 RECENT DEVELOPMENTS IN CCUS

3.2.1 Investment

The momentum behind CCUS has been building and it is becoming increasingly commercial and competitive in many countries. In 2022, investment in CCS more than doubled to hit a record high of $6.4 billion (BNEF, 2023). It was led by the USA, accounting for 45% of global investment. The generous policy incentives for CCUS in the USA should lead to more investment in projects in 2023. Investment in the Asia-Pacific surged to $1.2 billion in 2022 with projects under development in Australia and Malaysia, and the commissioning of a pilot project capturing 0.2 $MtCO_2/y$ at a petrochemical complex in China. EU funding for CCUS was mostly venture capital flowing into DAC companies such as Climeworks, which secured $650 million in April 2022. The EU also put much of its funding toward industrial decarbonisation with $420 million invested in cement and steel projects.

3.2.2 Pipeline of active projects

CCUS is on a strong growth trajectory after enduring some difficult years. Figure 3 shows the projects pipeline of commercial CCUS facilities since 2010 by CO_2 capture capacity (GCCSI, 2022a). There has

been an upward momentum in CCUS projects development since 2017, which accelerated in 2021. New CCS projects were added to the active pipeline each month in 2022. As of September 2022, a record 196 commercial CCUS facilities were in the project pipeline (*see* Table 1), including 30 facilities in operation, 11 under construction and 153 in development (GCCSI, 2022a). In 2022, there were 61 new facilities added to the project pipeline which raised CO_2 capture capacity of all CCUS facilities under development to 244 $MtCO_2/y$, a growth of 44% over the previous year.

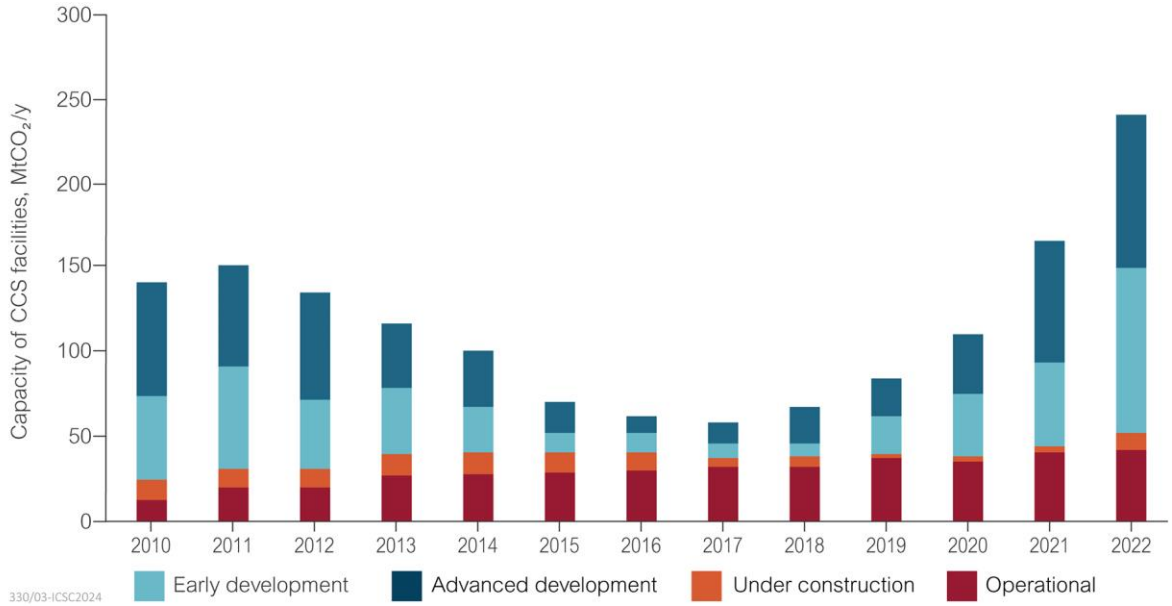

Figure 3 Project pipeline of commercial CCUS facilities since 2010 (GCCSI, 2022a)

TABLE 1 CO_2 CAPTURE CAPACITY OF COMMERCIAL CCUS FACILITIES, SEPTEMBER 2022 (GCCSI, 2022A)

	Operational	In construction	Advanced development	Early development	Operation suspended	Total
Number of facilities*	30	11	78	75	2	196
Capture capacity, Mt/y	42.5	9.6	97.6	91.8	2.3	243.9

* The number of facilities includes transport and storage projects which provide essential infrastructure for the industry to develop but they do not contribute to capture capacity tonnage figures so there is no double-counting of project capacities.

Increasingly, the focus for the application of CCUS is in the industrial or hard-to-abate sectors. The cement industry leads the way with public and private investments in cutting-edge capture technology and multiple ongoing projects. The world's first industrial-scale cement CCS project, the Brevik CCS project, is under construction at the Norcem cement plant in Brevik, Norway (Petersen, 2023). As part of the Longship project, funded by the state and Heidelberg Materials, this project started construction in January 2021. When fully operational in 2024, 0.4 $MtCO_2/y$ will be captured. Northern Lights is responsible for the transport and storage components of the project. Larger-scale cement CCS projects

are in early development by LafargeHolcim in the USA and Hanson Cement in the UK (GCCSI, 2022a). In the iron and steel sector, there is one operational CCUS plant at Emirates Steel in Abu Dhabi, UAE. This amine-based capture plant started operation in 2016 capturing 0.8 $MtCO_2/y$ from its host direct reduced iron (DRI) facility (GCCSI, 2022a). The captured CO_2 is used for EOR in the nearby oilfields. Chemicals production is another sector in which multiple CCUS projects are progressing at varying scales, including the production of hydrogen, ammonia and ammonia-derived fertiliser.

In addition, several power plants worldwide, particularly waste-to-energy plants, have announced plans to adopt CCUS. According to the GCCSI's (2022a) projects list, there are around 40 power plant CCUS projects under development, significantly boosting the expected CO_2 capture capacity by 2030. As these heavy industries and power plants often congregate, CO_2 networks have become a significant element in CCUS deployment. Among the newly announced projects during the second half of 2022, 11 large-scale projects are connected to the existing CCUS hubs, and six projects are associated with new CCUS hubs, accounting for more than 40% of total capacity in the active pipeline (S&P Global, 2023). The move from planning to action is starting to happen due to strategic partnerships and collaborations that use synergies and scale to reduce overall CCUS project costs and mitigate risks as explained in an International Centre for Sustainable Carbon (ICSC) report by Mills (2023).

Interest and engagement in DAC are growing, with billions of dollars in funding allocated to scale-up this technology and substantial new projects are being progressed. Eighteen DAC facilities are operational in Europe, the USA and Canada, all small scale capturing almost 0.01 $MtCO_2/y$ (IEA, 2022b). A 1 $MtCO_2/y$ DAC plant is in advanced development in the USA. Most of the plants are operated for testing and demonstration purposes and capture CO_2 for utilisation in carbonated drinks for example. Two store the captured CO_2 in geological formations. DAC is set to proliferate with multiple megatonne projects expected before 2030 given the unprecedented policy support and investment levels announced for this technology. However, the big challenge to its widespread large-scale application is that it costs more than other capture technologies due to the low CO_2 concentration in the atmosphere.

So far, captured CO_2 is used mainly for EOR. However, new technologies and ways of using or recycling CO_2 are emerging, and there is growing interest in them. Globally, private funding for CO_2-use start-ups reached nearly $1 billion over the last decade (IEA, 2020). There are carbon utilisation projects that convert captured CO_2 into value-added commercial products. For instance, the German polymer manufacturer Convestro opened its first commercial-scale plant in 2016 to produce polycarbonate polyol from CO_2 (Jasi, 2018). Also, the synthetic fuel production projects announced to come online in the next five years have a total capacity of 110 million litres (ML) (LUX Research, 2020). Most of these projects are not included in the projects pipeline reported by GCCSI as it focuses on carbon capture capacity build-out. There has been a significant development in CCU since the ICSC published *Developments in CO_2 utilisation technologies* in 2018 (Zhu, 2018). The latest developments are discussed in detail in the following Chapters.

3.2.3 CCUS in the coal power sector

Existing CO_2 capture facilities are mostly attached to industrial plants with natural gas processing plants having the largest capacity share as shown in Figure 4.

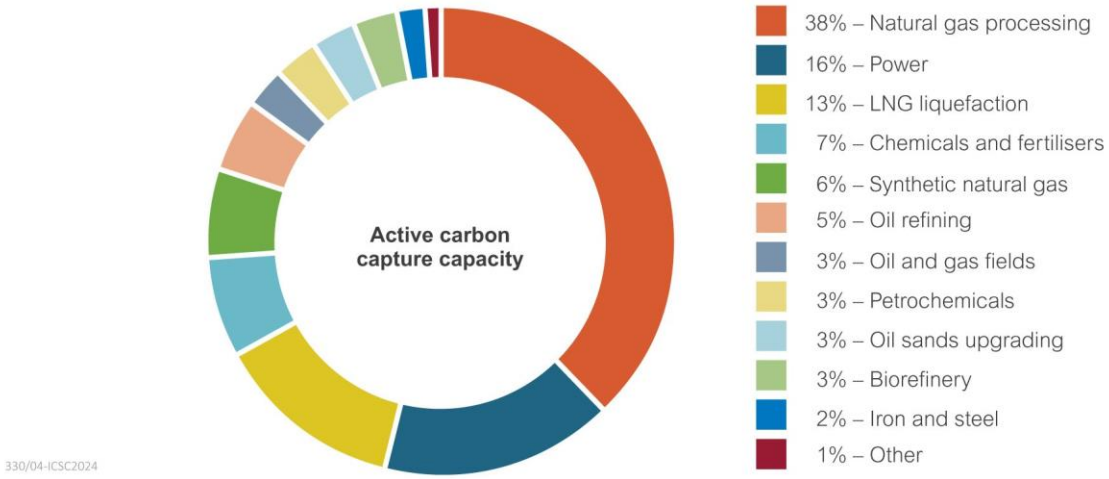

Figure 4 Distribution of active carbon capture capacity by sector in 2022 (Statista, 2023)

CCUS in the power sector is relatively new and faces many challenges. CO_2 capture technologies can be designed to be built into new power plants or retrofitted at existing facilities. Currently, there are three large-scale post-combustion CCUS facilities operating in coal-fired power plants; all are retrofits. The Petra Nova project in Texas, USA is the largest CCUS system installed on a coal-fired power plant capturing up to 1.4 $MtCO_2/y$ for use in EOR. Petra Nova uses an amine-based absorption process to remove over 90% of CO_2 from the flue gas from a 240 MW slipstream at NRG's W.A. Parish Unit 8. The facility operated successfully during its 2017-20 demonstration period and captured the targeted 95% of the total volume of CO_2 in 2019 (Kennedy, 2020). The operation of the Petra Nova project was suspended in May 2020 because low oil prices made its operation uneconomic. However, the high energy prices after the Russian invasion of Ukraine resulted in the restart of operations of the Petra Nova carbon capture facility on 5 September 2023 (JX Nippon, 2023).

The Boundary Dam CCUS project is the world's first commercial-scale, post-combustion capture facility on a coal-fired power plant. Installed on Boundary Dam Power Plant Unit 3 in Estevan (Canada) which has a net capacity (after CO_2 capture) of 110 MWe, the facility can capture 90% of CO_2, reducing the emissions from Unit 3 by 1 $MtCO_2/y$ (SaskPower, 2023). Cenovus Energy built a 66 km pipeline to transport the captured CO_2 to nearby oilfields for EOR. The unused CO_2 is stored underground 2 km from the plant (CCSKnowledge, 2023). The Boundary Dam CCUS project has been operational since 2014. As the UNFCCC (nd) states:

"SASKPOWER'S BOUNDARY DAM UNIT #3 IS NOW PRODUCING AFFORDABLE COAL POWER FOR MORE THAN 100,000 HOMES AND BUSINESSES FOR AT LEAST THE NEXT THREE DECADES AND DOING SO 10 TIMES MORE CLEANLY THAN OTHER COAL UNITS AND FOUR TIMES CLEANER THAN A COMPARABLE NATURAL GAS UNIT."

In June 2023, China commissioned its first large CCUS demonstration facility at China Energy's Taizhou coal-fired power plant in Jiangsu Province (CGTN, 2023). With a capture capacity of 0.5 $MtCO_2/y$ and a removal rate of more than 90%, this CCUS plant is the largest in Asia. The amine-based capture technology and engineering design have been optimised to improve the system efficiency and lower energy consumption. As a result, the cost of carbon capture is around CN¥250/tCO_2 (35 US$/$tCO_2$) while producing a stream of CO_2 with purity higher than 99.99%. China Energy has secured contracts with eight off-takers to ensure that all captured CO_2 can be utilised. The primary applications for the captured CO_2 include dry-ice manufacturing and the production of shielding gases for welding.

As mentioned in Section 3.1.1, J-Power has begun testing at its Osaki CoolGen Capture demonstration plant in Japan, enlarging the portfolio of capture technologies at operational coal-fired power plants. CO_2 is captured from a 17% slipstream of syngas from a 166 MW IGCC plant, with a capacity of about 400 tCO_2/d and a capture rate of over 90% (Osaki CoolGen, 2023). The captured CO_2 has more than 99% purity and will be supplied to a tomato cultivation demonstration field and other carbon recycling RD&D users (Misawa, 2021). Japan seeks to achieve highly efficient coal-fired power generation with near zero emissions and regards the integration of IGCC with CCUS and/or fuel cells as one of the next-generation technologies for low-carbon thermal power generation.

3.3 COMMENTS

Technologies for CCU can be applied to power plants and other hard-to-abate industrial processes, although there are challenges. While first-generation technologies are ready for commercial-scale deployment, new CCU technologies are in various stages of development, with the potential to significantly lower costs and improve performance. CCU continues to grow worldwide, and its deployment is scaling up rapidly. However, CCU is still in the early stages of technology and market development.

Decarbonising coal power generation using CCUS is possible. The operation of several large-scale demonstration plants has proven that combining CCU facilities with coal-fired power plants for low-carbon electricity production is technically feasible, and it can also be economically viable under the right conditions.

4 DEVELOPMENTS IN CARBON CONVERSION TECHNOLOGIES

CO_2 is a valuable commodity. It is widely used directly for EOR, carbonating beverages, as a coolant, a fire extinguisher, food preservation and for multiple other uses. CO_2 can also be used as a feedstock for the production of a wide variety of commercial substances including fuels, chemicals, polymers and building materials via multiple chemical and/or biological processes (conversion). There are concerted efforts from governments and private sectors worldwide to develop new opportunities to use CO_2 in a way that can support NZE goals while also driving industrial innovation, enabling a circular economy. Extensive R&D is underway to develop new technologies for converting CO_2 into valuable products. This chapter reviews the recent developments in CO_2 conversion technologies with a focus on those that are emerging in the commercial market or close to commercialisation. This updates the ICSC report by Zhu (2018).

4.1 PRODUCTION OF CO_2-BASED FUELS AND CHEMICALS

CO_2 can be combined with hydrogen to synthesise hydrocarbon fuels that could replace many of the fossil-based fuels available on the market such as methane, methanol, gasoline and aviation fuels. CO_2 can also be used to make chemical intermediates including syngas and methanol for the production of other chemicals. In particular, methanol is one of the main raw materials in the chemical and petrochemical industries with extensive applications as a solvent, fuel and chemical feedstock for the production of methyl, methacrylate, dimethyl carbonate, acetic acid, formaldehyde, methylamines, dimethyl terephthalate, and more (Saeidi and others, 2021). In addition, methanol can be used to produce ethylene and propylene via methanol-to-olefin processes. A detailed review of methanol production methods and global methanol market is available from the ICSC (Wiatros-Motyka and Lai, 2022). However, as CO_2 is a thermodynamically stable molecule with a low energy state, it requires a significant amount of energy to be activated. As a result, most of the R&D on CO_2 conversion focuses on the design of the appropriate catalysts to reduce the energy penalty.

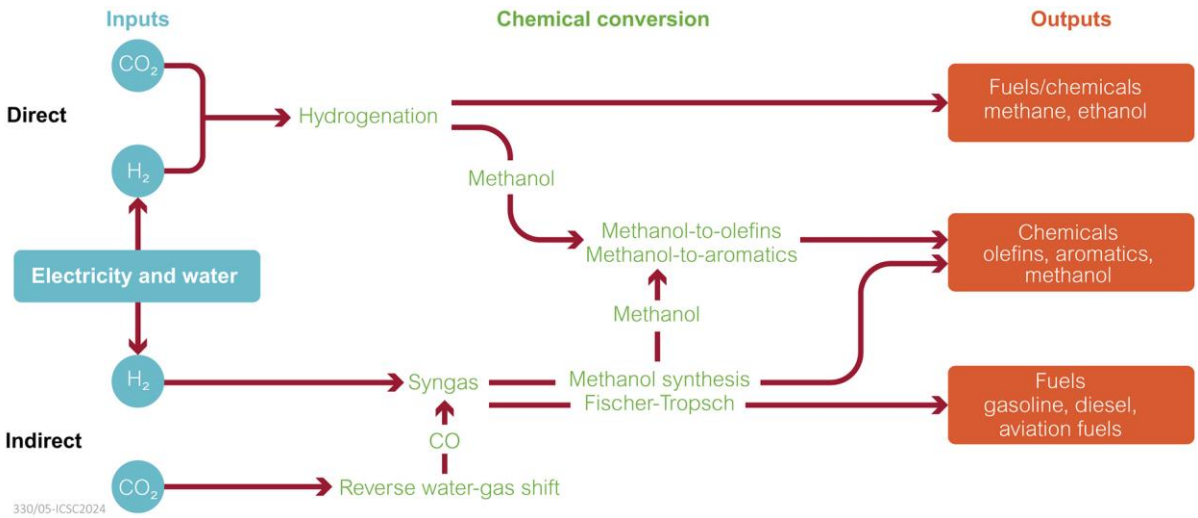

Figure 5 Mature conversion routes for CO_2-based fuels and chemicals production (IEA, 2019)

There are various chemical and biological pathways for CO_2 conversion. Many of them are still in an early stage of development, but some conversion technologies are mature and have been operational at an industrial scale whilst others are emerging in the commercial market. The most mature conversion pathways are:

- the direct conversion of CO_2 where CO_2 is catalytically converted in the presence of hydrogen into methane or methanol (hydrogenation or methanation), and
- indirect conversion in which CO_2 is first converted via reverse water-gas shift (RWGS) into CO, followed by the Fischer-Tropsch (FT) process or methanol synthesis process, as shown in Figure 5 (IEA, 2019).

The hydrogenation, Sabatier process, FT and methanol synthesis processes are technologically mature, while the RWS conversion has been successfully demonstrated on a small scale.

4.1.1 Direct hydrogenation or methanation of CO_2

When the H_2/CO_2 ratio equals 4, direct CO_2 hydrogenation results in methane (CH_4) formation through the well-known Sabatier reaction. In recent years, direct methanol production from CO_2 has gained attention due to the Power-to-X (P2X) concept. Numerous efforts to develop effective catalysts, together with designing advanced reactors for CO_2 hydrogenation, have resulted in some CO_2 conversion technologies reaching the early commercialisation stage, and there are commercial plants operational or in development in several places around the world.

Carbon Recycling International (CRI) of Iceland has been producing methanol at its George Olah facility using CO_2 captured from a nearby geothermal power plant since 2012 (CRI, nd; Zhu, 2018). The plant uses CRI's patented Emissions-to-Liquids (ETL) technology consisting of an alkaline electrolysis system and catalytic methanol synthesis process. Hydrogen is generated by the electrolysis of H_2O. The H_2 and CO_2 are mixed in a ratio of 3:1 and compressed to the target pressure,

followed by catalytic synthesis at an elevated temperature to produce methanol (*see* Figure 6). The plant recycles 5500 tCO_2/y and all energy used in it comes from the Icelandic grid, which is generated from hydropower and geothermal energy. The methanol produced is used as a blended component of gasoline and for further conversion to a diesel substitute.

In October 2022, the world's largest CO_2-to-methanol plant started production in China using CRI's ETL technology (CRI, 2022). Sited in Anyang, Henan Province (China), the new plant can capture 160 $ktCO_2$/y from existing emissions from lime production. The captured CO_2 is then reacted with hydrogen recovered from coke-oven gas to produce methanol with a capacity of 110 kt/y. CRI is carrying out a second project at the Sailboat Green Methanol plant in China. Located in Jiangsu province on the east coast of China, the plant will be integrated into the Shenghong petrochemical industrial park. The plant started operation in Q3 2023 and will recycle 150 $ktCO_2$/y and 20 ktH_2/y from other onsite processes to produce 100 kt/y of methanol. The methanol produced will be used to produce chemical derivatives, including sustainable plastics and ethylene-vinyl acetate (EVA) coatings for solar panels (Čučuk, 2023).

CRI's ETL technology was successfully demonstrated at a pilot scale (the FReSMe project) at a steel plant in Sweden in 2021 (CRI, nd). CO_2 captured from the steel blast furnace and processing hydrogen from by-product streams, in addition to its production by electrolysis, were used to synthesise methanol for use as a marine fuel. CRI, in partnership with the Norwegian renewable energy company Statkraft, is also developing an e-methanol production facility at a ferrosilicon plant in Finnfjord, northern Norway (CRI, nd). The plant will use CO_2 captured from the emissions of the Finnfjord ferrosilicon plant and hydrogen generated from water electrolysis driven by renewable power. The plant will recycle 150,000 tCO_2/y to produce 100,000 t/y methanol using ETL technology.

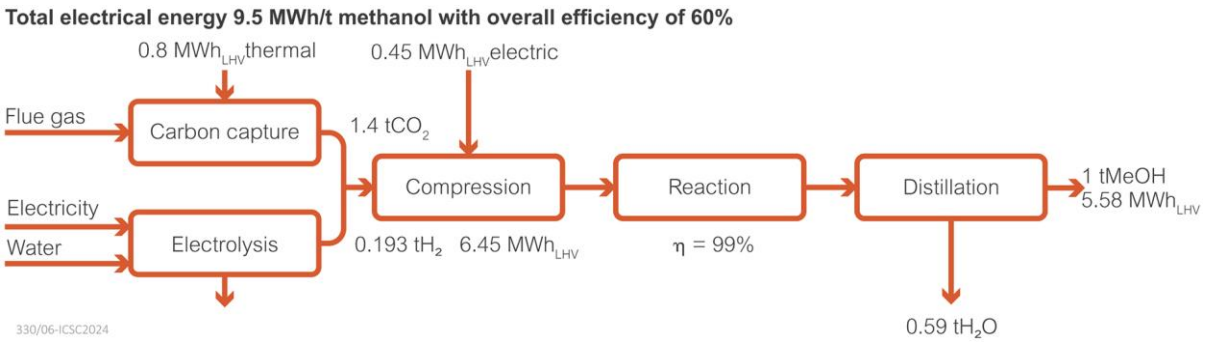

Figure 6 The ETL process with mass, energy balance and overall system efficiency (Stefansson, 2015)

Hitachi Zosen Inova's (HZI, Switzerland) EtoGas process has been demonstrated at a 6 MWe Power-to-Gas (PtG) plant in Werlte, Germany which started operation in 2013 (Zhu, 2018). The plant produces synthetic methane (e-gas) in a dynamic and intermittent operation using wind power. CO_2 from a biogas plant reacts with hydrogen produced by alkaline electrolysers via the Sabatier reaction to form methane, with a CH_4 content of >96%, for use as a motor vehicle fuel. The plant can produce

about 1000 t/y of e-gas, chemically binding some 2800 tCO_2/y. In 2022, another e-gas plant, owned by Energie Steiermark, started operation in Gabersdorf, Austria using the EtoGas process (HZI, nda). One MW proton exchange membrane (PEM) electrolysers driven by solar power are used to produce hydrogen which turns CO_2 from a biogas plant into methane. The methane produced is fed into the grid. HZI now provides two modular units that can be fully integrated into customers' infrastructure as a turnkey plant (HZI, ndb). The modular containerised units have a feed gas throughput of 2000 m^3/h and 6000 m^3/h, ready for outdoor installation.

Figure 7 3D model of FlexMethanol module skid (BSE Methanol, 2023)

BSE Methanol (a 2019 spin-off from BSE Engineering) markets its 10 MW or 20 MW FlexMethanol modules with pre-engineered skids, as illustrated in Figure 7 (BSE Methanol, 2023). FlexMethanol consists of four industrially available process steps: electrolysis, CO_2 scrubbing, methanol synthesis, and distillation. The modular approach enables fast project implementation at lower costs. The system has a fast-ramping rate, between 10–100 % load, to cope with potential fluctuations in the renewable electricity supply. The two modules have methanol production capacity of 8,000 and 16,000 t/y, respectively. Capacity can be increased by simply adding more skids. In 2020, BSE Methanol signed an engineering, procurement and construction (EPC) contract to supply a FlexMethanol 10 MW skid to a power-to-methanol plant in Antwerp, Belgium. In 2021, BSE Methanol signed an agreement with MAN ES to cooperate on the supply of FlexMethanol skids on the global market (Schweitzer, 2022).

Launched in 2009, Carbon Engineering (CE), a Canadian company, is commercialising its Air to Fuels (A2F) system after successful pilot scale demonstrations. A2F combines CE's DAC technology with water electrolysis and fuel synthesis to produce liquid hydrocarbon fuels. Descriptions of CE's DAC and A2F technologies can be found in Zhu (2018). In October 2021, CE announced that they and a consortium had begun preliminary engineering and design of a large-scale, commercial facility in British Columbia, Canada that would produce transportation fuel using CE's DAC and A2F technologies with a capacity of up to 100 ML/y (CE, 2021a). Construction was expected to begin in

2023 with operations targeted to commence around 2026. The initial engineering and design work received support from the British Columbia government with CA$2 million in funding from the Innovative Clean Energy Fund. Also in 2021, Air Canada and CE signed an agreement to explore commercial opportunities for sustainable aviation fuel (SAF), carbon removal and decarbonisation technology (CE, 2021b). In 2022, CE received millions of dollars in investments from Airbus and Air Canada to help advance and accelerate the scaling-up of CE's DAC and A2F technologies (CE, 2022).

There are several other commercial projects that are under development or have been announced. Established in 2021, the Nordic Ren-Gas Oy, in collaboration with other partners, is developing several power-to-gas projects in Tampere, Lahti, Kotka, Mikkeli and Pori, all located in Finland, to produce hydrogen, synthetic methane and district heating from the process waste heat (Ren-Gas, nd). At an estimated cost of €162 million, the Tampere project is expected to recycle 110,000 tCO_2/y to produce 35,000 t/y of methane when operation starts in 2026. The Tampere project has attracted investment from several sources and received a €45.8 million grant from the Finnish Ministry of Economic Affairs and Employment in December 2022, the largest green transition energy grant in Finland's history. The Lahti and Kotka projects will be a similar size to the Tampere one, but the Mikkeli and Pori projects are smaller with an expected synthetic methane production capacity of 12,000 t/y.

In May 2023, TotalEnergies and Tree Energy Solutions (TES) announced that they will jointly develop a $2 billion large-scale synthetic natural gas (e-NG) production plant in the USA (TES, 2023; Tani and Hook, 2023). The plant is expected to produce 100,000 to 200,000 t/y of e-NG. Hydrogen will be produced using 1 GW electrolysers powered by approximately 2 GW of wind and solar energy. The hydrogen will then be combined with CO_2 to synthesise e-NG using the Sabatier reaction. The resulting e-NG can be transported and/or liquefied and then sold like natural gas using existing infrastructure. The developers aim to reach a final investment decision (FID) in 2024. The project is expected to benefit from the tax credits provided by the IRA. TES has been in talks with potential off-takers of the e-NG in Germany and Japan.

Backed by Japan's New Energy and Industrial Technology Development Organisation (NEDO), Japanese companies have been active in R&D of CO_2 conversion technologies. INPEX Corporation of Japan has been developing CO_2 methanation technology since 2017. In 2023, INPEX and Osaka Gas Company jointly commenced construction of a large CO_2-methanation test facility (INPEX, 2023). The facility will be capable of producing 400 m^3CH_4/h, equivalent to the amount of methane consumed by about 10,000 households in Japan per day. The demonstration test is scheduled to begin in 2025 using CO_2 extracted from INPEX's Nagaoka Field Office. The methane produced will be fed into INPEX's natural gas trunk pipeline network.

NEDO has also been supporting R&D projects including technologies to convert CO_2 into liquid fuels, carbonate, and concrete products.

4.1.2 Indirect catalytic conversion of CO_2

Indirect conversion of CO_2 comprises two routes: the RWGS followed by the modified FT process, and RWGS plus the methanol-mediated route (Saeidi and others, 2021). In the RWGS-FT route, CO_2 hydrogenation results in CO formation (syngas) in RWGS and further hydrogenation of CO (FT process) leads to the formation of hydrocarbons. The FT catalyst promotes the conversion of syngas to hydrocarbons, and the distribution of the final products can be controlled by catalytic properties and reaction conditions. In the second route, methanol is the product of CO_2 hydrogenation, which can be converted to hydrocarbons via further hydrogenation. The RWGS-FT technology has been investigated more extensively, and some processes have reached commercialisation.

Figure 8 Atmosfair FairFuel Power-to-Liquid kerosene plant (Image credit: dpa picture alliance / Alamy Stock Photo)

Atmosfair's FairFuel plant in Werlte, Germany is a commercial-scale plant producing synthetic kerosene using renewable hydrogen and captured CO_2 (*see* Figure 8) (Atmosfair, 2021). Commissioned in October 2021, the plant produces 350 t/y of synthetic fuel oil through RWGS and FT synthesis. The fuel oil is then processed in a refinery into Jet A1, which is supplied to German airlines. The hydrogen is produced using 1.25 MW PEM electrolysers powered by wind energy, while the CO_2 is captured from a biogas plant and DAC. FairFuel is the first plant worldwide to produce fuel oil for synthetic kerosene, approved by ASTM for commercial aviation.

Topsoe, a Danish company, is also marketing its e-methanol production technology. It is currently providing EPC for Ørsted's FlagshipONE project which is under construction in Örnköldsvik, Sweden

(Ørsted, 2023; NS Energy, 2022). The P2X facility is expected to produce 50 kt/y of e-methanol as a marine fuel employing Topsoe's e-methanol synthesis. Hydrogen will be produced using 75 MW of Siemens' PEM electrolysers powered by an onshore wind facility, while CO_2 will be captured from a biomass-fired combined heat and power (CHP) plant. Construction of the plant started in May 2023, and it is scheduled to come online in 2025. Ørsted is also developing the 300 kt/y e-methanol Project Star in the US Gulf Coast area, and the Green Fuels for Denmark project in Copenhagen (State of Green, 2022; Ørsted, 2022). Green Fuels for Denmark has been recognised as an Important Project of Common European Interest (IPCEI) by the European Commission. It aims to reach a total electrolysis capacity of 1300 MW producing 275 kt/y e-fuel when fully developed. Topsoe is one of the technology partners on the project.

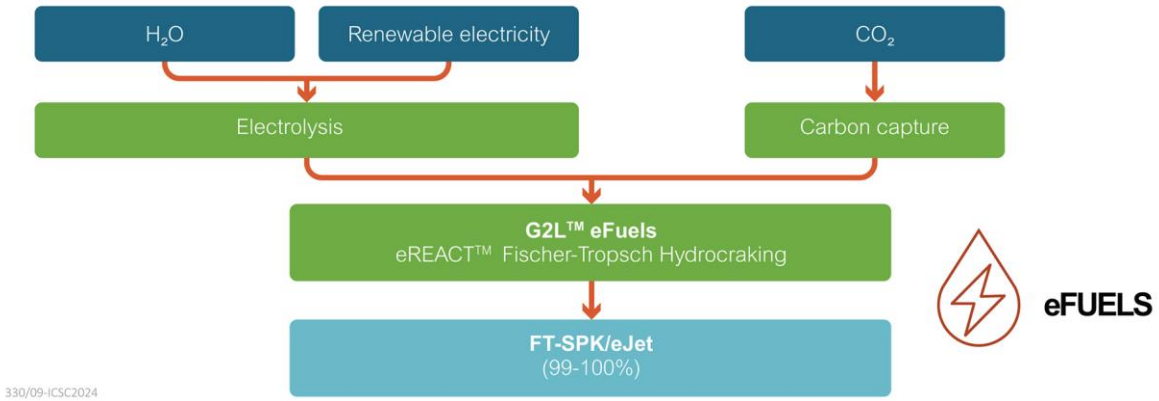

Figure 9 Process flow chart of an e-fuels plant with eREACT™ technology (Topsoe, 2023)

Topsoe has been developing the eREACT™ technology, an electrical reactor platform in which all the energy (heat and power) required by the production process of synthetic fuels is supplied directly by electrical power (Christensen and others, 2022). Figure 9 illustrates the process in an e-fuels plant with eREACT™ technology. Process heat is recovered and reused to optimise energy efficiency. By selecting operating conditions and catalysts, the process can be tailored to produce the desired final product such as diesel, kerosene or naphtha. A pilot plant was built in 2021 and demonstration tests have been conducted. The developer claims that the eREACT™ technology is ready for commercialisation.

A consortium comprising HIF Global, Porsche, Enel, ENAP, Siemens Energy, ExxonMobil and Empresas GASCO has built a commercial-scale Haru Oni demonstration plant in southern Chile (HIF, 2023). Haru Oni will produce 350 t/y methanol and 130,000 L/y gasoline using CO_2 from DAC and hydrogen produced by 1.2 MW electrolysers and powered by 3.4 MW wind energy. The plant was commissioned in December 2022. In the first stage, Porsche will use the e-fuels for its sports cars on racecourses and in vehicle trials. HIF Global has received approval to build another e-fuels plant in Matagorda, Texas. The facility expects to produce approximately 750 ML/y of synthetic renewable gasoline by 2027, equivalent to decarbonising over 400,000 vehicles.

Founded in 2015, the Norwegian company Nordic Electrofuel is developing E-fuel1, its first commercial e-fuels production plant, at Herøya Industrial Park in Porsgrunn, Norway (Nordic Electrofuel, nd). The plant will use the FT process to convert carbon emissions from metal or cement production or waste incineration into SAF. Hydrogen will be produced using alkaline electrolysers and the plant will be powered by Norway's grid electricity, 96% of which is generated by renewable hydropower. E-fuel1 has a design capacity of 10 ML/y and is expected to start operation in 2025. When operating, an emissions reduction of 25,000 tCO_2/y can be achieved. In June 2023, Nordic Electrofuel and P2X-Europe signed an agreement for a long-term supply of synthetic fuels with which P2X-Europe will take the e-fuels produced and upgrade it to SAF and other synthetic products (Nordic Electrofuel, 2023).

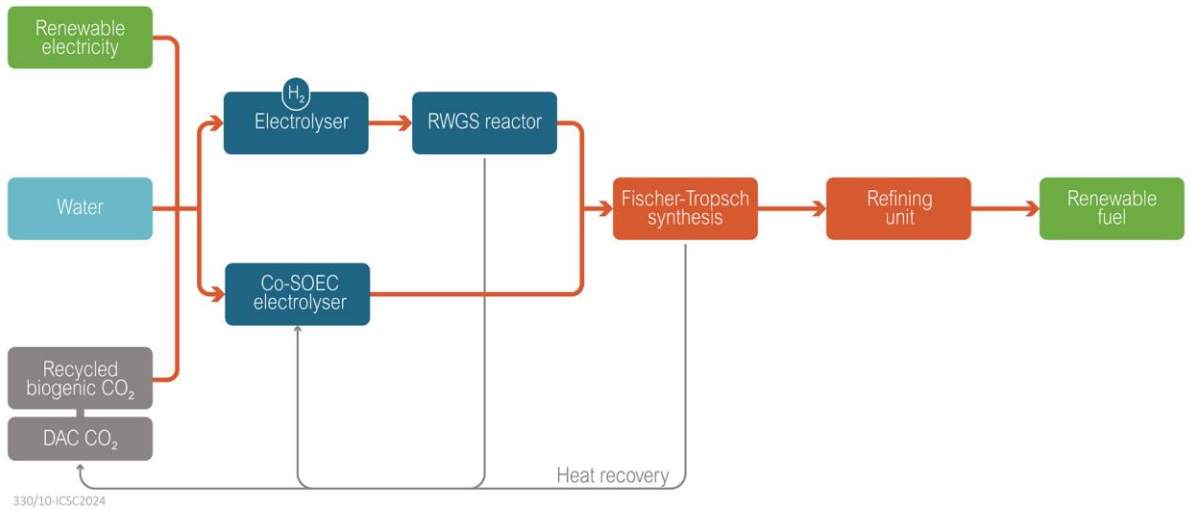

Figure 10 The technology approach taken by Norsk e-Fuel (Larsen, 2023)

Founded in 2019, Norsk e-Fuel is developing a full-scale e-fuel plant in Mosjøen, Norway (Larsen, 2023). The facility will use 100% renewable energy, water and recycled biogenic CO_2 and CO_2 from DAC, and turn them into SAF. Syngas is produced from CO_2 and water either using high-temperature co-electrolysis or via low-temperature electrolysis for hydrogen production, coupled with a RWGS reactor as shown in Figure 10. The syngas, a mixture of hydrogen and carbon monoxide, is then converted into hydrocarbons of different chain lengths through the FT process under the influence of pressure, temperature, and catalysts. Process heat will be recovered and reused to optimise energy efficiency. The synthetic crude can be refined into products of choice such as kerosene, diesel, petrol, waxes and other chemicals. In this case, kerosene is the final product. Construction is scheduled to start in 2024 and full-scale production is to begin in 2026. The plant will have a capacity of 50 ML/y (40 kt/y). In April 2023, Norwegian signed a strategic partnership agreement with Norsk e-Fuel, with the aim of securing a long-term off-take of SAF and an equity stake in the company.

There are other large commercial scale e-fuels projects under development, mostly in Europe. Some of the major projects are listed in Table 2. Liquid Wind, a Swedish e-fuels development company founded in 2017, and the initial developer of FlagshipONE, is developing FlagshipTWO and planning

a third e-fuels facility (Liquid Wind, 2023). Its investors include Alfa Laval, Carbon Clean, HyCap, Siemens Energy, Topsoe and Uniper. The FlagshipTWO facility, being developed in partnership with Sundsvall Energi, will be built in Sundsvall, Sweden, and aims to have a capacity of 100 kt/y methanol. CO_2 will be captured from the Sundsvall Energi's facility and combined with renewable hydrogen to synthesise methanol shipping fuel. Production is scheduled to start in 2026. A third facility of similar size to the one in Sundsvall is planned together with the energy company Umeå Energi at the Dåva cogeneration plant in Umeå. Liquid Wind aims to develop ten synthetic methanol facilities by 2030 in the Nordic countries.

The Danish company European Energy is building a P2X methanol facility in Kassø, Denmark (European Energy, 2023; Khosravi, 2023). The plant will be powered by the company's adjacent 300 MW solar park. Hydrogen will be generated using 50 MW PEM electrolysers supplied by Siemens Energy, and CO_2 will be captured from existing sources. When in operation, the plant will be able to produce 32 kt/y of synthetic methanol. Half of the output will be delivered to the Danish shipping company A.P. Moller-Maersk to fuel its first e-Methanol-driven container vessel. European Energy has not revealed which methanol synthesis process will be used.

TABLE 2 SOME MAJOR CO_2 TO FUEL PROJECTS THAT ARE OPERATIONAL, UNDER CONSTRUCTION, OR PLANNED

	Plant location	Product	Plant size, t/y	Start year
George Olah	Svartsengi, Iceland	methanol	4000	2011
Anyan	Anyang, Henan Province, China	methanol	110,000	2022
Sailboat Green Methanol	Lianyungang, Jiangsu, China	methanol	100,000	2023
Finnfjord e-methanol project	Finnfjord, Norway	methanol	100,000	n/a
Power-to-Methanol Antwerp	Antwerp, Belgium	methanol	8000	2023
Tampere project	Tampere, Finland	methane	35,000	2026
Kotka Project	Kotka, Finland	methane	35,000	2026
Lahti Project	Lahti, Kymijärvi, Finland	methane	35,000	2026
Mikkeli Project	Pursiala, Mikkeli, Finland	methane	12,000	2026
Pori Project	Kaanaa, Pori, Finland	methane	12,000	2027
Huron Clean Energy	Merritt, B C, Canada	e-fuels	103 ML/y	2026
TotalEnergies & TES e-NG Project	USA	methane	100,000–200,000	n/a
FairFuel Plant	Werlte, Germany	kerosene	350	2021
FlagshipONE	Örnköldsvik, Sweden	methanol	50,000	2025
FlagshipTWO	Sundsvall, Sweden	methanol	100,000	2026
FlagshipTHREE	Umeå, Sweden	methanol	100,000	n/a
Project Star	US Gulf Coast	methanol	300,000	n/a
Green Fuels	Copenhagen, Denmark	e-fuels	275,000	n/a
Haru Oni demonstration plant	Punta Arenas, Chile	methanol, gasoline	350 t/y (CH_3OH), 130,000 L/y (gasoline)	2022
E-fuel1	Porsgrunn, Norway	e-fuel	8000	2025
E-fuel2	Porsgrunn, Norway	e-fuel	200 ML/y	n/a
Norsk e-Fuel plant	Mosjøen, Norway	kerosene	40,000	2026
European Energy P2X methanol facility	Kassø, Denmark	methanol	32,000	n/a
Synkero Project	Amsterdam, The Netherlands	kerosene	50,000	2027
Zenid demonstration plant*	Rotterdam, the Netherlands,	kerosene	n/a	n/a
Hynovi project†	Montalieu-Vercieu, France	methanol	200,000	n/a
HIF Texas e-fuel Project	Matagorda, Texas, USA	gasoline	750 ML/y	2027

n/a not available

* the plant will demonstrate CO_2 conversion to fuel via syngas production by co-electrolysis of H_2O and CO_2 (from DAC) and then fuel synthesis through a modular FT reactor

† CO_2 will be captured from the Montalieu-Vercieu cement plant

4.1.3 Bioconversion of CO_2

Bioconversion using microorganisms such as bacteria and enzymes as biocatalysts is an attractive alternative method to sequester C1 compounds such as CO, CO_2 and CH_4 and convert them into value-added chemicals through their inherent metabolic pathways. Bioconversions have advantages over chemical processes as they normally operate under mild conditions and do not release any toxic by-products; chemical processes usually require expensive catalysts and operate at high temperatures and pressure making the overall technology expensive and energy intensive. In recent years, there have been significant breakthroughs in engineering bacteria and enzymes to utilise CO_2 and other C1 compounds as substrates for CO_2 fixation. Several systems for bioconversion of CO_2 are commercially available.

US LanzaTech has developed a biological gas fermentation process that produces fuels and chemicals from industrial waste gases (LanzaTech, 2023a; Zhu, 2018). The fermentation process uses rabbit-gut bacteria, a naturally occurring organism that grows on gases (rather than sugars as in traditional fermentation) to transform carbon-rich waste gases and residues into marketable liquid commodities in a continuous process. LanzaTech's proprietary bacteria can digest a wide variety of carbon-rich wastes to produce fuels and chemicals such as ethanol and 2,3-butanediol at high selectivity and yields. Ethanol is a basic building block of many materials, and it is also an alcohol that is blended with gasoline to lessen the volume of fuel used by cars. Having successfully operated multiple demonstration plants globally on steel mills off-gas and syngas from gasification of biomass and municipal solid waste, LanzaTech built the first commercial facility with Shougang Steel of China, which started operation in 2018. As of May 2023, there are five commercial plants in operation and two more to be commissioned in 2023 using LanzaTech's technology to convert carbon in industrial waste gases from diverse sources into ethanol as shown in Table 3 (LanzaTech, 2023a; 2023b). However, there is no information on the commissioning of the two plants at the time of publication, December 2023. In total, there are around 30 LanzaTech projects planned or proposed across the world. Currently, LanzaTech is constructing the world's first alcohol-to-jet fuel Freedom Pines Fuels facility in Georgia, USA. When completed later in 2023, the plant will produce 45.5 ML/y (10 million gallons per year) of SAF and diesel from low-carbon ethanol (LanzaJet, 2022). LanzaTech is also collaborating with CE to investigate the feasibility of a large-scale, commercial air-to-jet facility in the UK that will produce more than 100 ML/y of SAF using CO_2 from DAC (CE, 2021c).

TABLE 3 LANZATECH PROJECTS IN OPERATION OR UNDER CONSTRUCTION (LANZATECH, 2023A; 2023B)

Plant	Location	Status	Start year	Capacity, t/y ethanol	CO_2 source
Shougang Steel	Hebei, China	Operational	2018	46,000	Steel mill off-gas
Shoulang Jiyuan	Ningxia, China	Operational	2021	46,000	Ferroalloy off-gas
Shougang Guizhou Jinze	Guizhou, China	Operational	2022	60,000	Ferroalloy off-gas
NingXia Binze	Ningxia, China	Operational	2023	60,000	n/a
ArcelorMittal Steelanol	Ghent, Belgium	Operational	2023	64,000	Steel mill off-gas
IndianOil Panipat	Haryana, India	Under construction	2023	34,000	Refinery off-gas
Sekisui Demo Plant	Kuji City, Japan	Operational	2022	1/10th plant	Gasified municipal solid waste
Suncor Energies Demo Plant	Edmonton, Canada	Operational	2022	n/a	Gasified biomass
Freedom Pines Fuels	Soperton, Georgia, USA	Under construction	2023	45.5 ML/y of Jet fuel	

n/a = not available

Founded in 2014, Electrochaea has successfully scaled up a bioconversion technology from laboratory to industrial-scale pilot plants in Denmark and Switzerland to convert CO_2 into grid-quality methane (>97% CH_4 in the product gas) for energy storage and distribution. It is now commercialising its proprietary biological methanation process. Electrochaea's two-step biomethanation process starts with the production of hydrogen by water electrolysis, as illustrated in Figure 11. The hydrogen is combined with CO_2 and fed into the reactor which houses the biocatalyst, methanogenic archaea; the products of the reaction are methane and water (Electrochaea, 2023a). The process can operate in an intermittent mode with 0–100% load factor and has a rapid response to power input to accommodate the variable renewable energy (VRE). The developers claim that their patented biocatalyst has high selectivity and high mass conversion efficiency; fast reaction kinetics enabling scale-up to commercial application; tolerance for many contaminants typically found in industrial CO_2 sources such as oxygen, hydrogen sulphide and particulates; and the microorganisms are self-replicating and self-maintaining. One 10 MWe plant will convert 5700 $MtCO_2/y$ and produce 2.8 million m^3 synthetic methane, sufficient to heat 2400 homes or fuel 100–120 trucks and prevent this same amount of CO_2 from being released into the atmosphere from fossil resources.

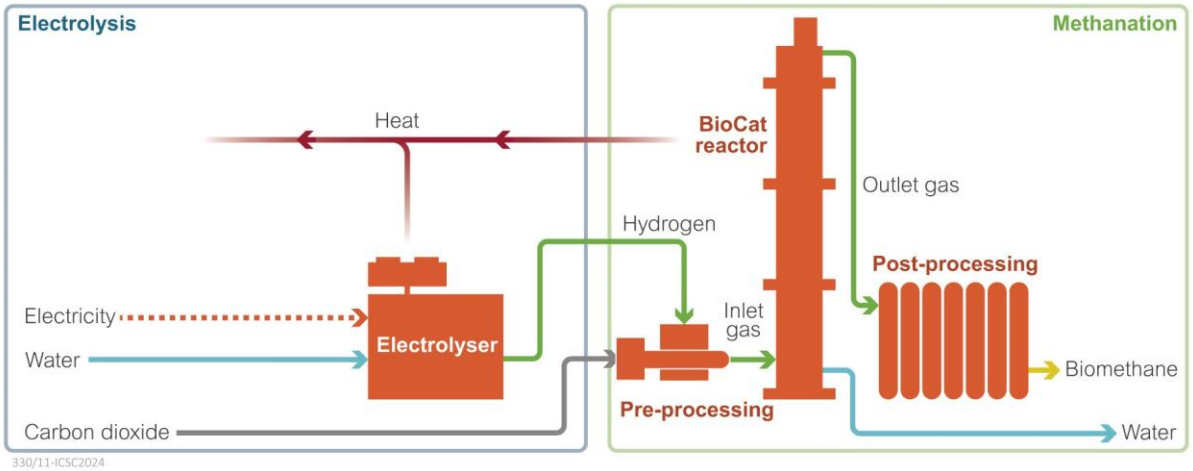

Figure 11 Electrochaea's two-step biomethanation process (Electrochaea, 2023)

In 2019, Electrochaea opened a third pilot plant at the USDOE's National Renewable Energy Laboratory (NREL) in Golden, Colorado, with support from Southern California Gas Company (PCEI, 2021). Electrochaea now has a pipeline of potential renewable methane projects as it moves forward with commercial roll-out in North America. Electrochaea's process has been selected by the Columbus project which is being developed in Wallonia, Belgium (Carmeuse, 2020). This project will concentrate CO_2 from an innovative type of lime kiln and combine it with renewable hydrogen to produce synthetic methane. The hydrogen will be produced by a 100 MW electrolysis unit, powered by renewable electricity. The Columbus project has received the go-ahead from the Walloon government and funding from IPCEI (Columbus, 2023; Dokso, 2023). The project is expected to be operational by the end of 2026. In 2023, a pan-European BioCat Consortium led by Electrochaea launched the BioCat Project, a 1 MW commercial-scale demonstration facility at the Avedøre wastewater treatment plant in Copenhagen, Denmark (Electrochaea, 2023b). The plant will use excess wind power to convert CO_2 in the biogas produced from the on-site wastewater treatment to produce methane for the Danish natural gas grid. Additional project objectives include the delivery of frequency regulation services to the Danish power grid and the recycling of heat and oxygen in the wastewater treatment processes.

In addition to the catalytic methanation EtoGas process, HZI has developed a biomethanation process using microorganisms known as BiON® (HZI, ndc). The process operates at ambient pressure and temperature and is highly flexible, operating between 0–100% load factor. The microorganisms used can handle diverse sources of feed gas from biogas and syngas to industrial emissions. The methane produced has a high purity and can be fed directly into the natural gas grid. In April 2022, an industrial scale power-to-gas plant using the BiON® process started operation in Zurich, Switzerland on the site of the Limmattaler Regiowerk Limeco utility (*see* Figure 12) (CNG-Mobilität, 2022). In the new plant, hydrogen was generated using 2.5 MWe electrolysers driven by renewable power. This hydrogen is fed into a bioreactor along with CO_2-containing waste gases from the existing waste and wastewater

treatment plants to synthesise methane. The plant can produce around 18,000 MWh/y of synthetic methane, saving up to 5000 tCO_2/y.

Figure 12 The first industrial power-to-gas plant in Dietikon, Zurich using the BiON® process (CNG-Mobilität, 2022)

There are numerous bioconversion processes in development. Many are commercial and more are ready for pilot- or commercial-scale demonstration. Most of these systems are for biomass feedstocks but some can also be applied to converting captured CO_2. For instance, the California start-up Invizyne Technologies has developed a biosynthetic process called SimplePath, a cell-free enzymatic platform for chemicals production using biomass or captured CO_2 (Invizyne, nd). Invizyne's platform has been applied to produce a variety of value-added products, with exceptional success in cannabinoids, biofuels and terpenes; concentrations orders of magnitude higher than those possible using yeast-based methods have been achieved. If this technology can be successfully demonstrated, it could provide a new biocatalytic platform for CCU.

4.2 PRODUCTION OF CO_2-BASED POLYMERS

CO_2-derived chemicals comprise a wide range of organic substances including plastics, fibres and synthetic rubber. A special group of chemicals are polymers, which are used in the production of plastics and resins. Currently, about 400 Mt/y of polymers are produced globally, and crude oil is the primary source of carbon for their production (nova-Institut, 2021). Some polymers can contain up to 50% CO_2 by weight (IEA, 2019). Part of the fossil feedstock can be replaced by CO_2 in the manufacturing process via copolymerisation of CO_2 and intermediates such as epoxides, or production of polycarbonates using CO_2 as starting material. There are several pathways to convert CO_2 into polymers including thermocatalytic, biological and electrochemical conversion. The thermocatalytic

conversion is the most mature technology, whilst bioconversion processes are emerging. Today, CO_2-based polycarbonates, polyurethanes and polythene are available on the market. Fossil fuel inputs are still necessary for polymer production through conventional manufacturing processes, but their use can be reduced by replacing part of it with waste CO_2, potentially saving on raw material costs and carbon emissions.

4.2.1 Thermocatalytic conversion

The Japanese Asahi Kasei Corporation has developed a non-phosgene polycarbonate production process using by-product CO_2 as a starting material. This process does not use toxic materials such as phosgene as a feedstock, and hence, reduces the generation of wastewater and waste products and has lower costs. Asahi Kasei opened its first commercial plant for polycarbonate production in 2002 in Taiwan. By 2021, they had licensed the technology to six companies in five countries and regions with a total production capacity of approximately 900 kt/y of polycarbonate, or 15% of the global overall polycarbonate production capacity of around 6 Mt/y (Asahi Kasei, 2021). The process has been further refined to manufacture high-purity ethylene carbonate and high-purity dimethyl carbonate (DMC) using CO_2 as one of the main feedstocks. Demand for high-purity ethylene carbonate and DMC is growing worldwide as components of the electrolyte solution of lithium-ion batteries which are used in smartphones and electric vehicles. Asahi Kasei concluded its first license agreement with this technology package in 2021.

In 2016, German plastics giant Covestro AG opened its first commercial-scale plant at Dormagen, Germany, to produce polycarbonate polyol using captured CO_2 as a raw material (Robinson, 2016). Polyols are the base of polyurethanes and other plastic materials. The plant has a capacity of 5000 t/y, and the final polyols contain 20% CO_2. The polyol is used for the commercial production of soft polyurethane for mattresses and upholstered furniture. In 2017, Covestro started to expand the process to increase the volume produced, the proportion of CO_2 used, and the range of chemicals produced. It developed a CO_2-based binder which has been used in sports subflooring; the first one of this type was fitted at a German-renowned hockey facility in Krefeld (Jasi, 2018). The application of CO_2-based polyols has been increased further, to the production of textile fibres and components for vehicle interiors. Together with German company Puren Gmbh, Covestro developed an initial prototype of a CO_2-based rigid foam polyol for the production of insulation boards for buildings that meet the key technical specifications of the market standard (Covestro, 2021). Covestro has been working to manufacture additional prototypes, enhance the properties of CO_2-based rigid foam insulation boards, and commercialise the final products.

US company Novomer Inc developed a catalytic system that transforms waste CO_2 into high-performance, low-cost polymers; it was first adopted commercially in 2014 (Zhu, 2018). With trademark Converge® polyols, they are a family of aliphatic polycarbonate polyols produced by copolymerisation of propylene oxide and CO_2 and contain up to 50% CO_2 by mass. These polyols can

be used in a variety of polyurethane formulations including coatings, adhesives, sealants, elastomers, and flexible and rigid foams. Unique performance enhancements have been observed in hardness, strength, and environmental resistance in these polyurethane applications. The company's initial products (1000 and 2000 molecular weight grade diols) are manufactured at a commercial-scale plant in Houston, Texas.

Since acquiring the Converge® polyol business and associated technologies from Novomer in November 2016, Saudi Aramco has been marketing Converge® polyols for various applications including flexible foam, rigid insulation foam for construction, industrial use, and appliances, as well as for coatings, adhesives, sealants, and elastomers (Aramco, 2018). In March 2023, India's Aether Industries signed a licence agreement with Aramco to manufacture and commercialise the Converge® polyols technology and product line (Worldofchemicals News, 2023; CNBCTV18, 2023). Aether Industries will be involved in the manufacture of four strategic products in the coatings, adhesives, sealants, and elastomers (CASE) field with a total volume reaching up to 1325 Mt per month.

Approximately 1.3 Mt/y of CO_2-based polymers production capacity was installed globally by 2022 (nova-Institute, 2023). There are several commercial plants in operation in China, run by different companies producing polymers from CO_2. Table 4 lists some of the major commercial CO_2-based polymers production plants in operation around the world.

TABLE 4 COMMERCIAL PLANTS FOR CO_2-BASED POLYMERS PRODUCTION WORLDWIDE (MODIFIED FROM NOVA-INSTITUT, 2021)

Company	Country	Capacity, t/y	Final products	CO_2 share, %	CO_2-based carbon content, %
Asahi Kasei and licence holders	Various	900,000	Aromatic polycarbonates	17.3	4.7
Covestro	Germany	5,000	Polycarbonates polyols	20	5.5
Empower Materials	USA	500	Various polyols	~*40	~11
Aramco	USA	5,000	PPC†, PEC‡	43	~12
Jiangsu Zhongke Jinlong-CAS Chemical	China	10,000	PPC polyols	40	11
Jilin Boda New Materials	China	50,000	PPC or PEC	~40	~11
Inner Mongolia Mengxi High-Tech Group	China	3,000	Various polyols	~40	~11
Taizhou BangFeng Plastic	China	30,000	PPC	~40	~11
Nanyang Zhongju Tianguan	China	5,000	PPC	~40	~11

* average weighted CO_2-based carbon content
† propylene carbonate
‡ poly-ether carbonate

In addition to the several successfully implemented technologies reported on the market, more processes for the diverse use of CO_2 for polymer production are in development and are already commercial or close to commercialisation. A British company, Econic Technologies, has developed and successfully demonstrated a catalytic system that can incorporate up to 50 wt% of waste CO_2 into polyols (Econic, 2023a). Econic intends to manufacture the polymers and to sell the innovative catalysts and license their technology and processes to large-scale chemical manufacturers. In June 2022, Econic reached an agreement with a Chinese polyol and polyurethane producer, Changhua Chemical Technology Company, to develop CO_2-based polyurethane products to be manufactured in China and sold under license in China and worldwide (Econic, 2022a). Under the licence, Changhua will build the first dedicated production plants for these products. Also in 2022, Econic signed a licence agreement with Indian Manali Petrochemicals to build a demonstration facility, followed by retrofitting Manali's more than 12,000 industrial-scale reactors with Econic's proprietary process. In June 2023, Econic and Monument Chemical, a leading speciality chemical manufacturer, announced a licensing agreement to develop and grow CO_2-based polyurethanes in the USA (Econic, 2023b). With Econic's technology, Monument will upcycle waste CO_2 into polyols for high-performance foams, laminates, coatings, and elastomers for use in automotive, furniture, mattress, construction, and industrial applications. Monument will begin production based on the Econic process in late 2023.

4.2.2 Biocatalytic conversion

Newlight Technologies, USA has developed a biological system to produce Polyhydroxybutyrate (PHB), a degradable biomaterial with the trademark AirCarbon™ (Newlight, 2023; Zhu, 2018). Newlight Technologies' process comprises three steps: capture, extraction and polymerisation. First, concentrated methane or CO_2 emissions from sources such as farms, landfills, water treatment plants and energy facilities, are directed into a bioconversion reactor. The carbon emissions are combined with Newlight's biocatalyst, which extracts carbon out of methane or CO_2. Finally, carbon, oxygen and hydrogen are re-assembled to form PHB, a high-performance thermoplastic material that matches the performance of a wide range of petroleum-based plastics but costs less. The developers claim that when made with renewable power, the production of AirCarbon™ is a carbon-negative process.

In September 2020, Newlight Technologies opened its first commercial-scale plant, Eagle 3, to produce AirCarbon™ using air and greenhouse gases (Bioplastics, 2020). The material produced at the facility is used in the two new brands which the company has launched: Restore Foodware and Covalent Fashion. In 2022, Newlight and CNX Resources (USA) announced a 15-year agreement to capture and utilise methane emissions to produce AirCarbon™ (Bioplastics, 2022a). Newlight also announced plans to build a carbon capture-based manufacturing facility in partnership with Long Ridge Energy Terminal, USA. Newlight's customers and partners include global brands such as Shake Shack, Nike, Target, H&M, Ben and Jerry's, Sumitomo, US Foods, and Sysco.

As described in Section 4.1.3, LanzaTech has developed a bioconversion process to make ethanol and monoethylene glycol (MEG) from waste carbon. LanzaTech has established partnerships with major brands such as Unilever, L'Oréal, On, Danone, Zara, and Lulumelon to use the CO_2-derived ethanol and MEG (polymer precursors) for manufacturing packaging items, shoes, and textiles (Bioplastics, 2022b).

4.2.3 Electrochemical conversion

A Dutch company Avantium has developed an electrochemical process called Volta Technology which it is commercialising (Avantium, 2023; Zhu, 2018). The process converts CO_2 to high-value products and chemical building blocks such as formic acid, oxalic acid, and glycolic acid. The latter two are key building blocks for polyesters and other materials, allowing the production of CO_2-negative plastics. Avantium installed a mobile Volta Technology container unit at an RWE power plant in Germany in 2021. During a six-month period, the container operated for 1000 hours with the world's largest gas diffusion CO_2 conversion cell and successfully converted CO_2 directly from the power plant into potassium formate which is used in anti-freeze products, heat transfer fluids, water treatment chemicals and fertilisers.

Avantium installed a second Volta unit at a Titan cement factory in Greece. During a three-month period, the facility converted CO_2 from a carbon capture facility at the cement factory into formate. A third demonstration unit successfully converted CO_2 into oxalic acid. In a proprietary second, separate process step, it is then turned into glycolic acid. By combining the glycolic acid with some lactic acid, polylactic-co-glycolic acid (PLGA), a carbon-negative polymer can be produced. In May 2023, Avantium was awarded a €1.5 million grant by the EU Horizon Europe programme to demonstrate the conversion of CO_2 from biogas produced at wastewater treatment plants into PLGA (Bioplastics, 2023).

4.3 PRODUCTION OF CO_2-BASED BUILDING MATERIALS

CO_2 emissions can be effectively utilised through CO_2-carbonation (CO_2-mineralisation) processes to form various products and/or carbonate precipitates, as it is a thermodynamically favourable reaction. CO_2-carbonation is a natural process in which CO_2 reacts with calcium or magnesium and iron to form carbonates that can store CO_2 permanently. While the natural process of forming carbonates takes many years, CO_2-carbonation as a technology pathway accelerates the carbonation process and reduces the reaction time to minutes. Multiple feedstocks for CO_2 carbonation are being explored including natural rocks containing magnesium- or calcium-rich silicate minerals and alkaline industrial wastes such as steel slag and fly ash. Industrial wastes are attractive because they are available in industrial regions.

Figure 13 illustrates how CO_2 can be incorporated into concrete materials. CO_2 mineralises with alkaline reactants to produce inorganic materials: aggregates, bicarbonates, and building materials such as cement and concrete, with a lower CO_2 footprint compared to those produced by traditional

methods. Production of carbonate materials can provide an effective long-term storage option for CO_2, especially for use in the construction industry which represents a large potential market for CO_2-based products.

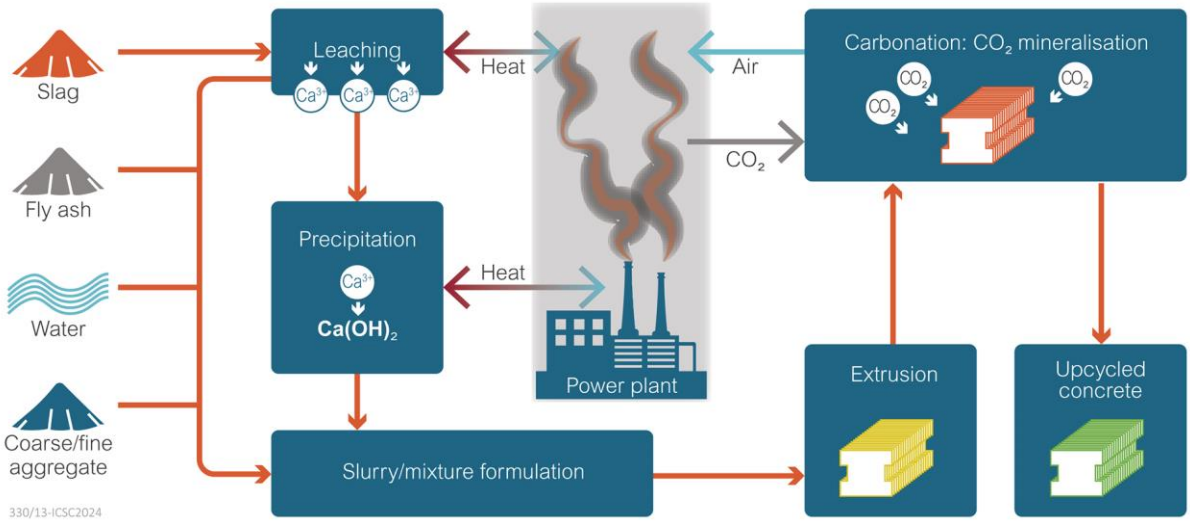

Figure 13 Production of higher-performance construction materials using CO_2 emitted from power or industrial facilities (OFECM, nd)

4.3.1 Wastes and minerals carbonation with captured CO_2

A British company, Carbon8 Systems, has developed Accelerated Carbonisation Technology (ACT) to treat a wide range of industrial wastes that contain calcium or magnesium with captured CO_2 to produce carbonates that can be used as lightweight aggregates, fertiliser, or other building materials (Carbon8, 2023; Krämer, 2021). ACT offers a fast and cheap way to process natural minerals and wastes such as contaminated soil, steel slag, cement kiln residues, water treatment sludges and mining tailings. Carbonation takes place during a 15-minute process. Over 120 residue types have been tested, and mix designs developed. Carbon8 has built three commercial plants in the UK, each with a capacity of treating up to 40,000 t/y of Air Pollution Control residues (APCr) (Carey, 2022). The first plant was commissioned in early 2012 in Brandon, Suffolk, (Zhu, 2018). It has a capacity of 30,000 t/y of APCr (a hazardous waste from municipal incineration solid waste), producing over 65,000 t/y of carbonated lightweight aggregate. Most of the aggregate produced at the ACT Brandon plant is used by Lignacite in both their dense and medium-dense aggregate blocks. These plants use pure CO_2 captured primarily from fertiliser manufacturing plants which is delivered by tanker (Carey, 2022; Carbon8, 2023). Since 2018, Carbon8 has developed a modular containerised system 'CO_2ntainer' which can be plugged in to extract CO_2 directly from flue gas. ACT is housed inside the CO_2ntainer, enabling the production of aggregate for a variety of applications including concrete blocks, road filler and green roofing substrate, as well as fertilisers. A CO_2 container can treat up to 12,000 t/y of residues. The CO_2ntainer system can take flue gas that contains 10 % of CO_2 by volume, which is typical for flue gas from cement and power plants. The system has been successfully demonstrated at a waste-to-energy plant in the Netherlands. A CO_2ntainer system is operational at Vicat's Montalieu cement plant

in France producing aggregate using cement bypass dust and CO_2 from the cement plant emissions. The APCr-based aggregate produced using ACT contains 4–15 wt% of CO_2 and has properties similar to those of conventionally produced aggregates. In 2021, Carbon8 teamed up with FLSmidth to market Carbon8's ACT in the global cement industry using FLSmidth's network.

Founded in 2013, the Australian start-up MCi Carbon (formerly Mineral Carbonation International, MCi) developed a mineral carbonation technology, which transforms minerals and waste materials and captured CO_2 into commercial products that can be used in cement, concrete and plasterboard, for example (*see* Figure 14) (MCi, 2023). The process can achieve CO_2 uptake of 7–12% with little external energy required during the process. MCi Carbon is also working with various manufacturing and product companies globally, conducting joint trials and assessments of new product formulations. MCi Carbon has constructed three generations of Carbon Plants, including the Global Reference Pilot Plant in Newcastle, Australia, which was publicly launched in July 2017. MCi Carbon's carbonation technology has been successfully demonstrated at pilot scale and the company is now focused on its commercialisation. MCi Carbon aims to lock one billion tonnes of CO_2 into usable products by 2040. MCi Carbon has received multimillion dollars of government funding to scale up its technology. In May 2021, MCi signed a partnership with Japanese giant ITOCHU Corporation to integrate MCi's technology into ITOCHU's global network. ITOCHU, having bases in 62 countries, will identify and develop market applications for MCi's technology.

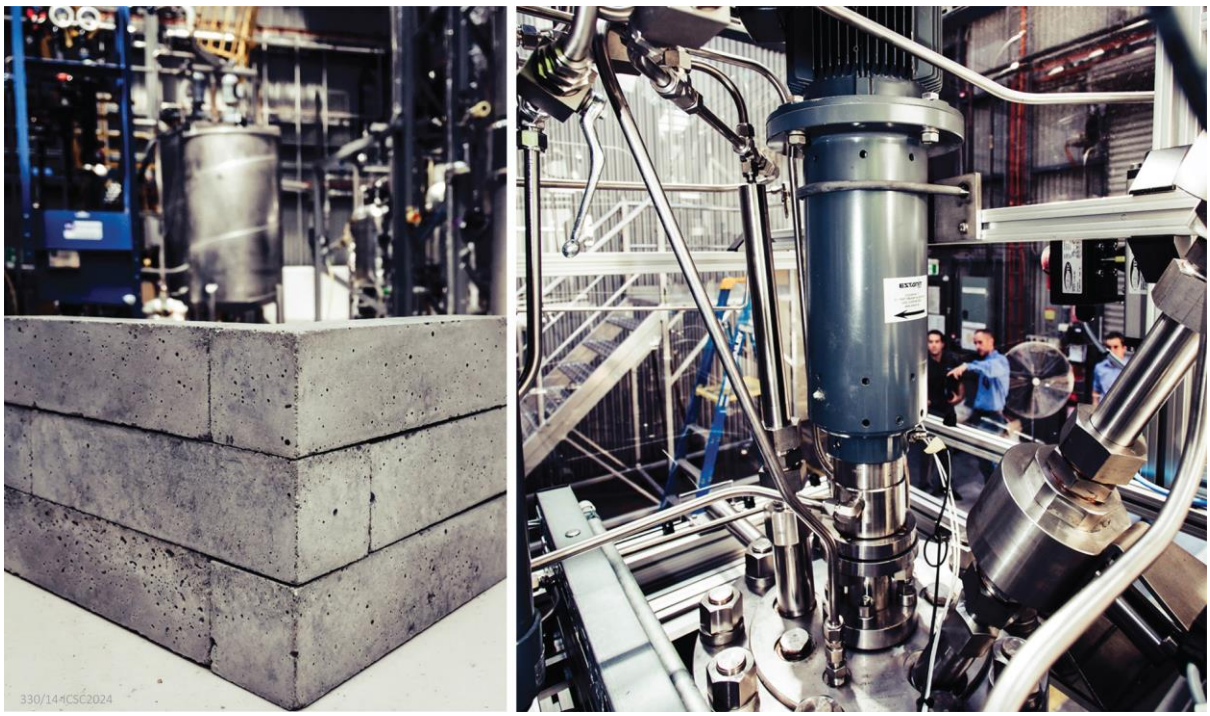

Figure 14 Carbonate bricks produced using MCi Carbon's process (MCi, 2023)

A Canadian start-up, Carbon Upcycling Technologies (CUT), developed a technology that captures CO_2 from point sources such as cement kilns and power plants, absorbs it into a solid powder and converts it into a family of nanoparticles with many potential applications (CUT, 2023). The solid feed

used in the patented process can be graphite, petroleum coke, coal or fly ash, for example. Through its portfolio of CO_2-derived solid nanoparticles, CUT has technically validated its solutions for use in plastics, coatings, epoxy, adhesives, concrete, lithium-ion batteries, pharmaceutical industries, and consumer products. In 2017, CUT successfully commercialised a corrosion-resistant coating utilising its nanoparticles. CUT recently launched a brand, Oco, comprising a range of CO_2-based commercial products including wall panels and vessels made from CO_2-enhanced fly ash, and several other products made using CO_2-enhanced graphitic nanoplatelets. CUT has received investment from organisations such as Clean Energy Ventures, CEMEX and Oxy Low Carbon Ventures (a subsidiary of Occidental), and also formed partnerships with companies such as BURNCO, Lafarge Holcim and A^3&Co® to promote the commercial-scale deployment of CUT's technology in the cement industry.

After four years of R&D, a spinoff from Columbia University, GreenOre CleanTech LLC, is marketing its technology to process steel and iron slag, power plants' fly ash and cement waste with waste CO_2 to produce calcium carbonate, iron oxide, silica, alumina, and possibly rare earth concentrates, depending on the feed. The company uses a technology that converts industrial waste into valuable chemical products such as filler for paper, paint, plastics and rubber (GreenOre, 2023). CO_2-containing flue gas is fed into the process directly as a reactant. Joined by Baotou Steel in Inner Mongolia, China, GreenOre launched the world's first 1000-tonne commercial demonstration plant, which will treat 100,000 t/y of steel slag. The facility commenced a trial in July 2023 and successfully produced the first batch of carbon-negative, high-purity calcium magnesium carbonate which will be used in the production of degradable plastic bags and PVC pipes. The product can generate 13.68 $/t (100 ¥/t) of profits. When the project is complete, Baotou Steel will have a slag mineralisation plant with a capacity of 420,000 t/y of steel slag, and CO_2 emissions from the steel plant will be reduced by over 100,000 t/y. The developers claim that for one tonne of slag treated, 1.25 tCO_2 emissions can be avoided. As China generates almost 90 Mt/y of steel slag, the application of this technology to process it could potentially reduce the life cycle direct and indirect CO_2 emissions by more than 100 MtCO_2/y.

Founded in 2019, Californian-based Fortera has developed the ReCarb™ process that re-carbonates calcium oxide to produce Reactive Calcium Carbonate™, a natural cement with the ability to stabilise it in a dry powder form, only activating its cementitious properties when it is wetted (Fortera, 2023). Fortera's process starts with the conversion of limestone ($CaCO_3$) to lime (CaO) at around 950°C. The lime is then dissolved into a proprietary solvent. In the next step, called the ReCarb™ process, CO_2-containing flue gas from cement or power plants, for example, is fed directly into the solution, giving rise to a precipitated reactive calcium carbonate. The developers claim that the ReCarb™ process reduces CO_2 emissions by 60% compared to traditional cement production. A pilot scale facility is installed at the Lehigh Hanson Redding cement plant in northern California and began commercial production in 2022. Fortera is commercialising its ReCarb™ process and has expanded into Europe.

Blue Planet's Geomimetic® process combines waste CO_2 with demolished and returned concrete to manufacture synthetic limestone ($CaCO_3$) aggregate that can be used to make carbon-neutral and carbon-negative concrete. Blue Planet claims that its process can work with a wide variety of CO_2 emission sources including thermal power plants, cement, iron and steel plants, chemical plants, refineries and DAC (Blue Planet, 2023). Flue gas containing CO_2 at concentrations as low as 5% can be used directly without needing purification and liquefaction. Every tonne of Blue Planet aggregate contains 440 $kgCO_2$. Concrete made with Blue Planet aggregate meets or exceeds all ASTM strength tests. For alternative wastes such as steel slag, cement kiln dust, fly ash, and APCr the Blue Planet process can produce a valuable byproduct such as supplementary cementitious materials. Blue Planet has attracted several investors including Chevron, Mitsubishi, Holcim and Knife River Corporation.

In September 2022, Calpine Corporation, an electricity generator, and Blue Planet commenced operation of a demonstration facility in California, transforming power plant emissions into synthetic limestone aggregate. CO_2 from Calpine's 580 MW natural gas power plant is fed through a pipeline to Blue Planet's facility adjacent to the Global Innovation Center, where the CO_2 and other components are turned into aggregate. The aggregates produced could be used as building materials in construction projects in California. Following the demonstration phase, the goal is to build a commercial-scale plant in Pittsburg, California, with a capacity of 500,000 t/y of synthetic aggregates, capturing and sequestering 175,000 tCO_2/y.

4.3.2 CO_2 curing of concrete

Concrete is the most widely used material in the world after water. Cement is used to bind concrete together, giving it the required strength and durability for a wide variety of applications. CO_2-cured concrete can lower cement input leading to reduced CO_2 emissions and costs while having a similar or better performance compared to conventionally produced concrete. CO_2 curing of concrete is an emerging technology.

Several companies have developed their concrete curing process or the CO_2-cured concrete and are marketing it, including the Canadian CarbonCure Technologies and Solidia Technologies in the USA. Both processes use pure captured CO_2 delivered to concrete plants or construction sites in pressurised tanks. CarbonCure's process can be applied to ready-mix concrete production or precast concrete plants and be integrated with the concrete producer's batching system without impacting normal operations (*see* Figure 15). The CO_2 is injected into fresh concrete during mixing and the carbonation process takes place under atmospheric pressure, without the need for special curing chambers. Solidia's process, however, is for precast concrete production. Both companies report lower costs and improved product performance (CarbonCure, 2023; Solidia, 2023; Zhu, 2018). The Solidia process has a shorter curing time and can lower water consumption by 80%. It is estimated that a cubic metre of concrete made using the CarbonCure process could hold around 3.5 $kgCO_2$. Existing plants can easily be retrofitted to enable CO_2 curing. The CarbonCure process has already been installed in over 400

concrete plants in North America, Asia, and Europe. Solidia also supplies its technology and CO_2-cured concrete to the commercial market. In May 2023, Solidia announced that it would build its first commercial manufacturing facility for dry-cast concrete products in Texas (Solidia, 2023). Solidia anticipates the facility will come online later in 2024.

Figure 15 A concrete mixer with CO_2 injection at a construction site (CarbonCure, 2023)

A US company, CarbonBuilt (formerly known as CO2Concrete LLC), developed a CO_2 curing process that directly converts CO_2 from power plants or other emitters (with no requirement for capture or purification) into precast concrete and concrete masonry products (CarbonBuilt, 2023). The first field demonstration of the technology at scale took place at the Wyoming Infrastructure Authority's Integrated Test Center, where the team successfully sequestered waste CO_2 from a coal-fired power plant into more than 10,000 concrete blocks. A second demonstration was carried out at the National Carbon Capture Center in Alabama using CO_2 emissions from a natural gas-fired turbine. These demonstrations highlight the technology's ability to accommodate a wide range of dilute CO_2 streams. CarbonBuilt's process has been retrofitted into one of the production lines owned and operated by Blair Block in Childersburg, Alabama, which began commercial production in May 2023. The blocks, which reduce embodied carbon by 70–100% and cost no more to produce than traditional concrete, will be used in the construction of several municipal projects across Alabama. In March 2023, CarbonBuilt received funding from 4 Corners Carbon Coalition, a network of local governments, to build a fully integrated DAC-to-concrete production facility at the Block-Lite manufacturing plant in Flagstaff, Arizona.

Founded in 2016, a Canadian company CarbiCrete has developed a CO_2 curing technology for the production of cement-free, carbon-negative concrete (CarbiCrete, 2023). The system uses steel slag to replace cement as a binding ingredient in precast concrete products. The curing process involves

the injection of CO_2 into an absorption chamber where it reacts with the steel slag within the fresh concrete. This curing process takes 24 hours and stores 3 $kgCO_2$ per concrete masonry unit (CMU). The developers claim that its technology can be easily retrofitted to any precast concrete plant. The mixing of steel slag with aggregate and water and the subsequent step of block formation are carried out using the standard equipment already in place. CarbiCrete licenses its technology to concrete manufacturers who can integrate it into their existing production processes for CMUs and precast panels. CarbiCrete oversees the retrofit required to implement the process and manages the installation and integration of the absorption chamber as well as the CO_2 tank that is stored onsite. The technology is currently being deployed at its pilot facility housed at hardscape manufacturer Patio Drummond's precast plant in Quebec with the capacity to produce 25,000 CMUs per day. In May 2023, CarbiCrete and POINT.P, a Saint-Gobain brand, signed a cooperation agreement to commercialise CarbiCrete technology in France.

4.4 COMMENTS

CO_2 is a valuable commodity and can be captured and used as a raw material and to replace fossil fuels in the production of synthetic fuels, chemicals and polymers, building materials, and other products. Technologies for converting CO_2 to an array of commercially established products are emerging, but most are still in the commercialisation stage and face commercial and regulatory challenges. An increasing amount of CO_2 is captured from fossil fuel and biogenic point sources, as well as from DAC. Commercial and pilot-scale CCU projects are multiplying around the world.

There is considerable interest in CO_2-derived synthetic fuels for the aviation and shipping sectors. Strong RD&D activities have led to a number of projects being developed, mainly in Europe. Most of the projects emphasise sustainability by using renewable energy in their production.

CO_2-based polymers are commercially available from traditional suppliers and startup companies using innovative approaches. Polymers can incorporate up to 50 wt% of CO_2 and can be used to produce a wide variety of products used in daily life. Intensive R&D on the chemical conversion of CO_2 into different types of polymers is ongoing. This could provide one of the solutions to the environmental issue caused by plastic waste. RD&D of technologies for converting CO_2 into high value-added products via carbonation has also progressed rapidly.

Bioconversion of CO_2 is attracting great interest and shows high potential for the production of fuels, chemical building blocks and polymers. Biocatalytic conversion of CO_2 to form methane and ethanol has seen tremendous growth in recent years with the latter being produced on a commercial scale for fuel applications and in the chemical and polymer industry.

Reduction of CO_2 via photocatalytic and electrocatalytic conversion represents a potentially promising alternative for obtaining a variety of useful products. There has been extensive R&D activity in the field. Many improvements have been made, especially in electrocatalytic conversion, which led to the

creation of several startup companies. However, finding effective electrodes or catalysts for selectively converting CO_2 into desired products continuously and at high rates remains a key challenge. Most of the processes are still in the early stage of development although a few appear to be ready for pilot scale test/demonstration.

The market for building materials from the carbonation of industrial wastes with captured CO_2 and CO_2-cured concrete has developed rapidly. It has shown that CO_2-derived aggregates and concrete can have properties similar to, or better than, those of conventionally produced counterparts and hence, can be used for the same applications. Most of the processes use pure CO_2, but some, such as Carbon8's ACT and GreenOre's process, can use low-grade CO_2 or flue gas directly from industrial processes or power plants. This has the advantages of capturing and utilising emitted CO_2 in one system and lowering the costs. A group of companies are supplying various carbonation and CO_2-curing technologies on the market and more companies are commercialising their novel processes. CO_2-curing processes have been adopted in concrete production facilities, and several plants for CO_2 mineralisation of wastes for commercial production of aggregates and other valuable products are in operation around the world.

In short, there are many pathways to convert CO_2 into a range of valuable commercial products. A broad portfolio of carbon utilisation technologies has been investigated and some are advancing towards maturity and can increasingly be found in commercial applications.

5 POTENTIAL CONTRIBUTION OF CCU TO ACHIEVING NZE

There is increasing interest in using CO_2 as a feedstock to produce value-added products as an alternative to storing it underground. This is driven partly by goals to increase sustainability, lower emissions, and move towards a circular economy. CO_2 is already used extensively in fertiliser production, for EOR, and other conventional applications such as in food processing, fire-extinguishers and cooling systems. This chapter assesses the potential market for CO_2-derived products and their competitiveness with conventional counterparts. The environmental benefits and role of CCU in achieving NZE and in a circular economy, as well as drivers and barriers to CCU deployment, are discussed.

5.1 THE POTENTIAL SCALE OF DEPLOYMENT

5.1.1 Market uptake potential

In general, CO_2-derived products have material properties that are comparable to, or better than, their fossil-based counterparts. The future markets for CO_2-derived products are difficult to evaluate as they will be influenced by many factors such as technological developments, the technoeconomic competitiveness of CCU, decarbonisation targets and the development of supporting policy and regulatory frameworks. In theory, CO_2-derived products can replace their conventional counterparts in the market and be used for the same applications without needing major alterations to existing infrastructure. which indicates the size of the market that CCU products could penetrate.

TABLE 5 PRODUCTION OF SELECTED CONVENTIONAL PRODUCTS IN 2019/2020 (IEAGHG, 2021A)

	Commodity	Market size, Mt/y
Fuels	Middle distillate hydrocarbons	3,000
	Synthetic methane	2,000
	Dimethyl ether (DME)	500
	Ethanol	100
	Methanol for gasoline blending	30–170
Chemicals	Methanol as chemical intermediate	80
	Formic acid	1
	Dimethyl carbonate (DMC)	0.09
Polymers	Polycarbonate	4
	Polyols for polyurethane	12
Building materials	Concrete	30,000
	Manufactured aggregates	1,000

Table 5 shows that fuels represent one of the largest potential markets for CCU products, owing to the high volumes, high market value and the global trend towards sustainable fuels. Although there is a growing deployment of renewables and electrification to decarbonise economies, chemical fuels will continue to play a major role in many sectors, especially shipping and aviation. Building materials have the biggest market size because of the vast volume produced. However, due to the higher CO_2 uptake rates, synthetic fuels show the greatest potential for CO_2 use by volume, followed by building materials and chemical intermediates (*see* Figure 17 on page 66).

Potential markets for various CCU products and the CO_2 avoided that could be achieved under different scenarios have been assessed by the IEAGHG (2021b), based on today's global markets. They found that, as shown in Figure 16, replacing the existing methanol market with CO_2-derived methanol would give a total demand of 100 Mt/y. Methanol can be upgraded to both fuels and chemicals, allowing a broad range of possible end-uses. In the competitive case where CO_2-derived methanol penetrates new markets to the following extent: 3% of current medium- and heavy-duty freight trucks and 30% of polyolefins, plus the entire existing methanol market for chemical end-uses, the total market for CCU methanol would be 160 Mt/y. In the ambitious case, CO_2-derived methanol penetrates 100% of the freight truck market and 80% of the polyolefins market, alongside the existing methanol markets. This would generate a market of 825 Mt/y for CCU methanol. If today's market demand is met by CO_2-derived methanol in these three scenarios, CO_2 emissions could be reduced by 186, 297, and 1537 Mt/y, respectively, which could be achieved provided that renewable hydrogen and electricity are used for methanol production. Also, in the competitive case, synthetic fuels penetrate 3% and 40% of existing medium- and heavy-duty freight trucks and aviation fuel markets respectively, generating a market demand for CO_2-based middle distillates of 148 Mt/y. In the ambitious case, CCU products penetrate the entirety of these markets, with a demand of 903 Mt/y. If the entire market for conventional middle distillates were to be replaced with CCU products, then the demand for CCU products would be 2900 Mt/y.

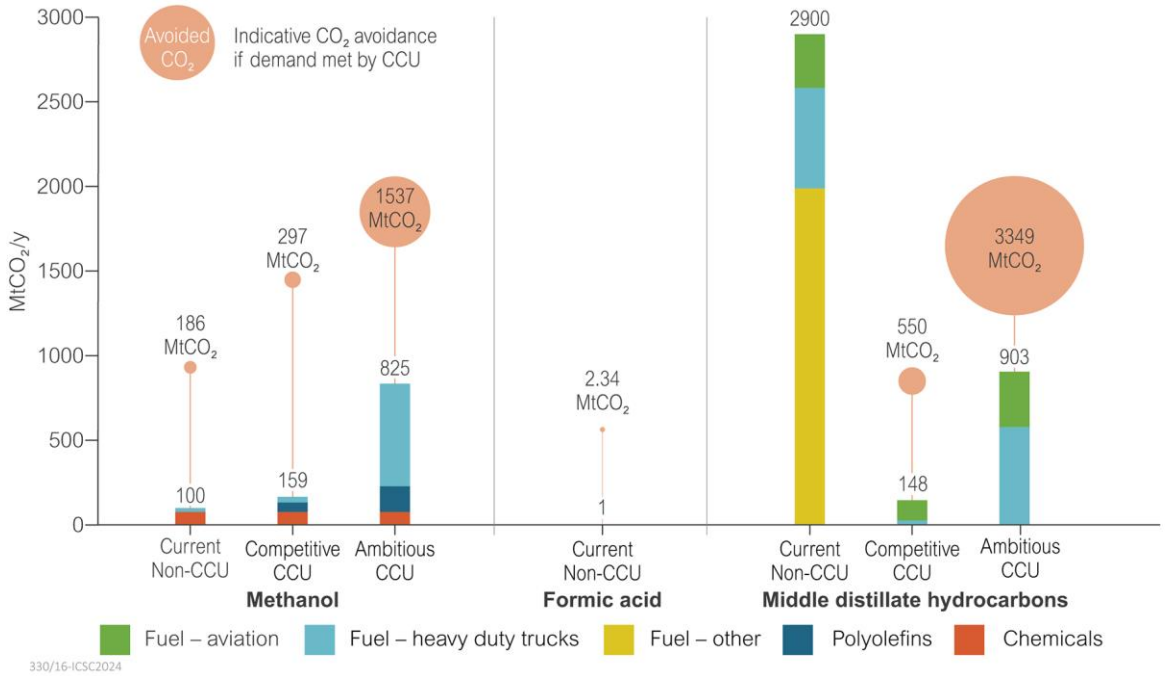

Figure 16 Potential market for selected CCU products and the resulting CO_2 emissions reductions (IEAGHG, 2021b)

5.1.2 CO_2 utilisation opportunities

As most CO_2 conversion technologies are still in the early stage of RD&D, their technical performance and cost-effectiveness are not yet well understood. Their scalability and potential will be affected by many factors which are often highly specific to different applications and sectors, making assessment of the climate change mitigation potential of CO_2 use extremely difficult, both for individual products, and CCU technology as a whole. This is reflected in the wide-ranging global estimates of CO_2 demand by CCU, from 1 to 7 $GtCO_2/y$ in 2030 (IEA, 2019). The IEA regards the figure of 7 $GtCO_2/y$, which equates to nearly 20% of the global CO_2 emissions today, as exceedingly optimistic.

Figure 17 shows the IEA's estimates of the theoretical potential for maximum CO_2 use by CO_2-derived products and the relative climate benefits that could be achieved if all conventionally produced products were replaced (IEA, 2019). Synthetic fuels present the greatest market potential with demand for CO_2 of >5 Gt/y, followed by building materials and chemical intermediates with CO_2 demand of 1–5 Gt/y. Building materials have the greatest CO_2 mitigation potential, mainly because of their low energy requirements for the CO_2 conversion process and the permanent retention of carbon in the product. This is followed by fuels and chemical intermediates. The use of CO_2 in polymer processing and greenhouses has the lowest potential, both in terms of potential for CO_2 use (up to 1 Gt/y) and in relative climate change mitigation benefits.

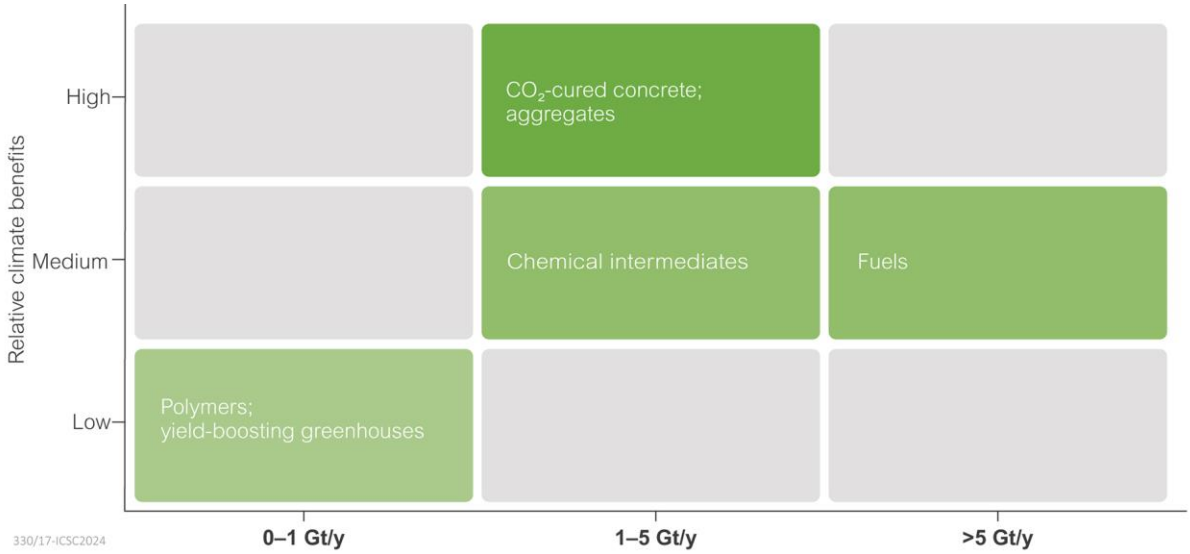

Figure 17 Potential use of CO_2 in various CCU products (IEA, 2019)

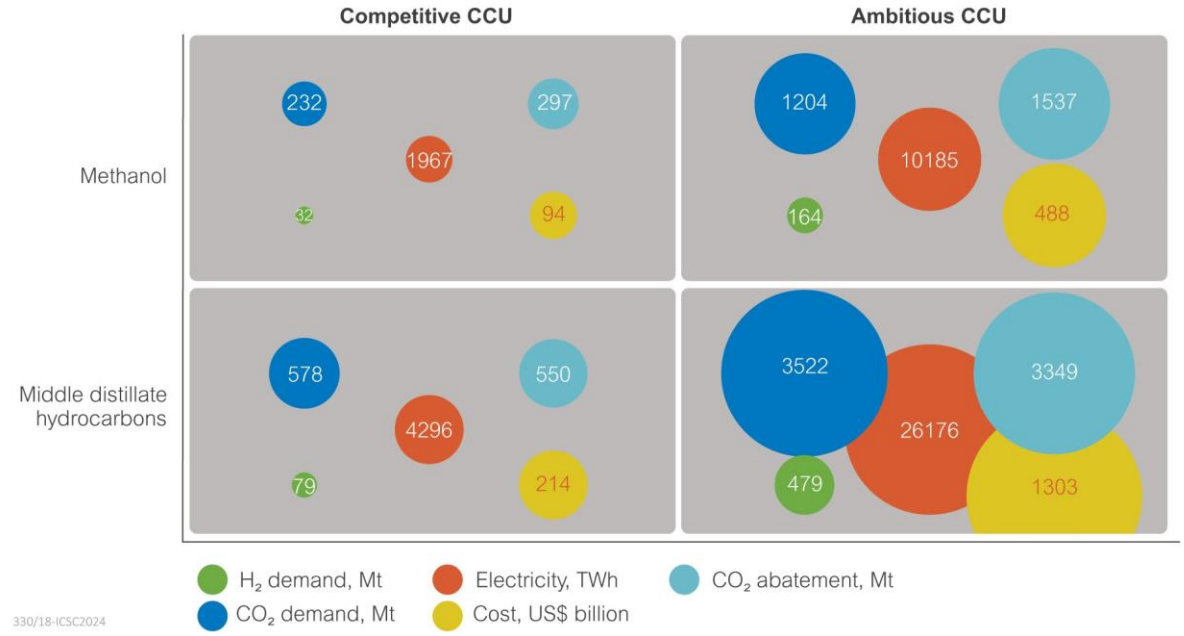

Figure 18 CO_2 mitigation benefits with associated costs, resource demands and energy required for levels of market penetration of CCU products (IEAGHG, 2021b)

In a comprehensive study by the IEAGHG (2021b) as described in Section 5.1.1, CO_2 avoidance could be achieved with different levels of market penetration by CO_2-based fuels and the associated costs, resource demands and energy required are assessed. The results, as shown in Figure 18, indicate that in the competitive case, 232 $MtCO_2/y$ would be used to produce synthetic methanol and 578 $MtCO_2/y$ for CO_2-based middle distillates. These will rise to 1204 $MtCO_2/y$ for CCU methanol and 3522 $MtCO_2/y$ for CCU middle distillates in the ambitious case.

Apparently, the overall scale of CO_2 utilisation is moderate in relation to the total CO_2 emissions that can potentially be captured and used. Therefore, where changes in sector outputs due to CCU product

substitution may lead to decreases in CO_2 emissions, these effects will not have material impacts on the availability of CO_2 as feedstock for CCU.

5.1.3 Competitiveness

The economic competitiveness of CCU products depends on their production costs compared to their conventionally produced counterparts and other low-carbon alternatives. The cost of a CO_2-derived product is influenced by many factors including the costs of technology, energy, CO_2 and other raw materials. The conversion of CO_2 to fuels and chemicals usually requires large amounts of hydrogen which has high production costs, especially when it is produced from electrolysis (Zhu, 2023). While capital costs for catalysts are typically product-specific, the origins and prices of hydrogen and CO_2 are relevant for almost all CO_2-derived fuels and chemicals and will be key determinants of the overall cost of these products. If CO_2 or hydrogen need to be transported to the producer, this would incur a significant additional cost depending on the distance and transport mode such as truck, pipeline or ship. The competitiveness of CO_2-derived products is also affected by the cost of emissions. For example, a high carbon price can enable CO_2-derived products to become cost-competitive with their fossil-based counterparts.

The main cost components for the production of CO_2-derived fuels and chemical intermediates are capital expenditure, hydrogen, electricity, and CO_2 feedstock. The scale-up of CCU deployment requires access to large-scale and affordable CO_2 sources, renewable hydrogen and renewable electricity. Many of the CO_2 conversion routes for producing fuels and chemicals use hydrogen produced from electrolysis, meaning that costs are highly dependent on the cost of renewable electricity. Almost all the conversion processes require pure CO_2. The costs of CO_2 include capture, purification and transport, which range from 15–120 $\$/tCO_2$ depending on the emission source (IEA, 2019). The cost of CO_2 from DAC will be much higher ranging from roughly 94–232 $\$/tCO_2$. As a result, the current cost of producing CO_2-derived fuels is generally multiple times higher than the market price, although there are large regional variations.

The higher costs of CO_2-derived fuels and chemicals are also due to the low yields and high catalyst costs of some of the lesser-developed routes. In a comprehensive study commissioned by Concawe and Aramco (2022), techno-environmental and economic assessments of various e-fuel pathways produced in different regions of the world (Europe, Middle East and North Africa) in 2020, 2030 and 2050 were conducted. They found a strong correlation between energy requirements for renewable e-fuel production and associated costs. The cost of renewable electricity accounts for between 50–65% of the production costs. The estimated costs of e-fuels in Europe (including production, storage and transport) in 2030 and 2050 are shown in Figure 19. Based on the assumptions made, the costs of e-fuels supply in Europe are higher than those for crude oil-based fossil fuels. This is the case even in 2050, taking into account improvements in technology and decreases in electricity costs. In 2050, the costs of e-fuels supply ranges between 1.4 $€/L_{diesel\ equivalent}$ for synthetic methanol and

2.6 €/$L_{diesel\ equivalent}$ for kerosene produced from syngas using FT process compared to 0.8 €/L of fossil oil-based diesel. Similar trends are also reported by the IEAGHG (2021b).

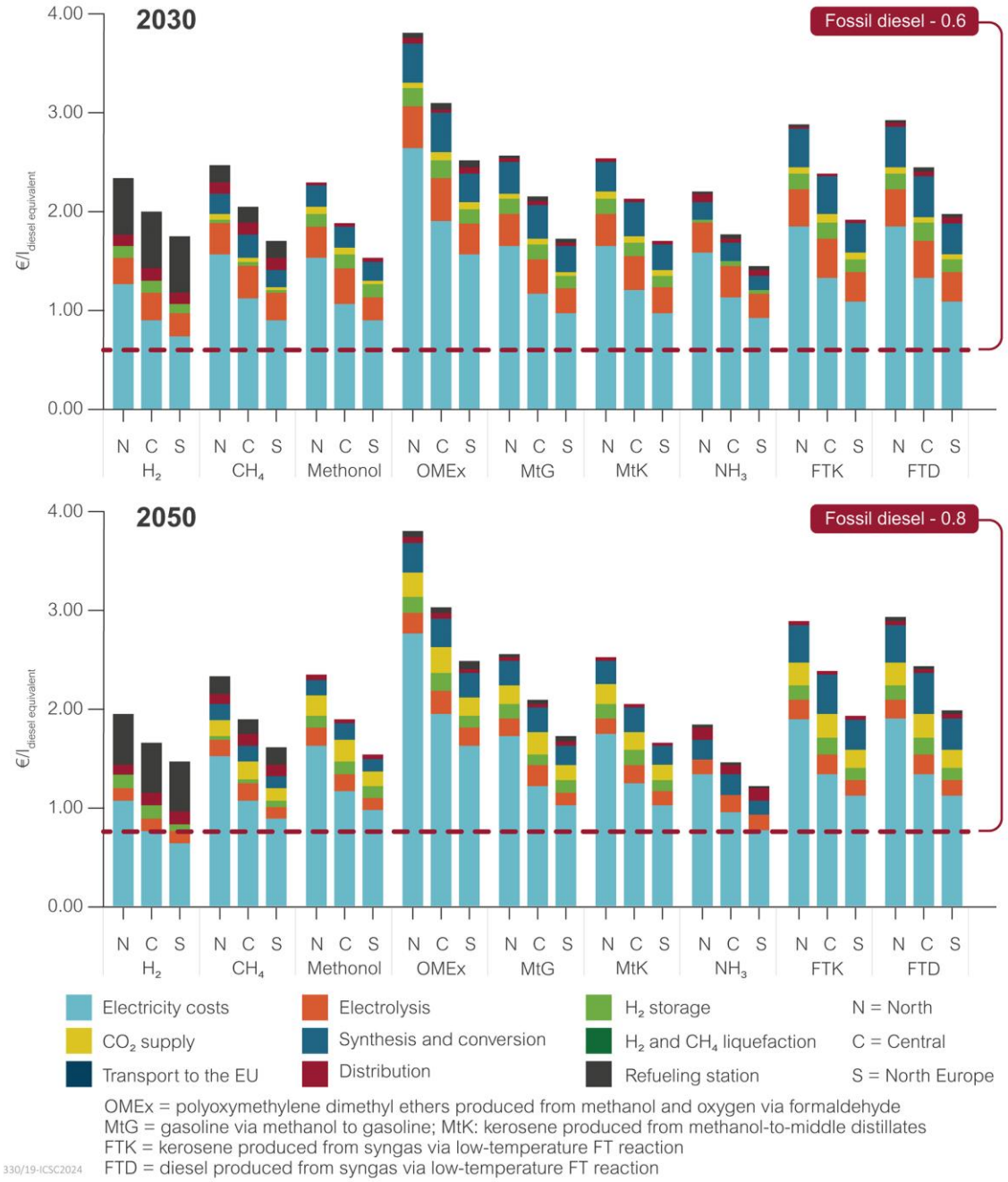

Figure 19 Estimated costs of e-fuels produced in Europe in 2030 and 2050 (Concawe and Aramco, 2022)

It is expected that the production costs of CCU products will decline over time, mainly due to capital cost reductions and the availability of cheaper renewable electricity and feedstock CO_2. However, CO_2-derived methane and liquid fuels such as diesel or aviation fuels, will continue to be uncompetitive in the absence of a stringent CO_2 price regime and/or policy support. However, the IEA (2019) considers that in the long term, CO_2-derived methanol may become competitive in more regions, depending on local methanol market prices.

The competitiveness of CO_2-based polymers depends on the production costs, the specific application of a polymer and the market price of the final products. CO_2-derived polymers can be cost-competitive in the market, due to the relatively low energy requirements for their production and their high market value. Several companies produce and supply polymers from CO_2 commercially (*see* Section 4.2), and certain CO_2-based polymers that are cheaper than fossil-based counterparts have been reported (Alberici and others, 2017; Zhu, 2018). The low-carbon nature of these products could further improve their competitiveness.

CO_2-cured concrete could have lower production costs and higher strength than its conventional counterparts. The cost savings mainly result from the shorter curing time required and reduced demand for cement in the concrete mix. There has been a rapid development in the commercialisation of CO_2-cured concrete in the past few years. Some companies working on concrete curing technologies claim to be able to mitigate emissions via CO_2 curing at a CO_2 abatement cost of less than 6 $/t$CO_2$ (Alberici and others, 2017).

The main value proposition for companies to mineralise waste materials using CO_2 is to reduce waste disposal costs while creating a saleable CO_2-containing product for construction and other sectors. Some technologies such as Carbon8's ACT and the GreenOre process can act as a carbon capture device absorbing CO_2 in the flue gas at emission points such as power plants, steel and cement producers. This means that building materials and other products from CO_2 mineralisation of wastes can be produced at a competitive cost because the manufacturer may be paid to take the CO_2 from emitters and the wastes for disposal. A detailed techno-economic analysis by CSIRO (2023) indicates that CO_2-derived mineral carbonates such as mineral aggregates for building materials can abate emissions and even create negative emission products at levelised costs that could be competitive in today's commercial market in the Northern Territory of Australia. Given the right circumstances, for instance, in an industrial area where CO_2 emission sources and suitable industrial wastes as feedstock as well as potential product off-takers are available, a positive business case exists where revenue can be created via the use of CO_2 mineralisation products.

5.2 ENVIRONMENTAL BENEFITS OF CCU

5.2.1 Carbon emissions mitigation potential

For almost all CCU applications the potential to contribute to carbon emissions reductions will be central to their future deployment. Assessing such potential is challenging because it depends on many factors which are difficult to determine. In recent years, initiatives have been made to develop standardised technoeconomic assessment and life cycle analysis (LCA) methodologies for CCU (IEA, 2019).

The Methanol Institute published a report that includes LCAs of various methanol production pathways using the European Renewable Energy Directive (RED II) methodology (Hamelinck and

Bunse, 2022). The results are shown in Figure 20. It found that eMethanol produced using water electrolysis and captured CO_2 powered by solar PV electricity has a substantially lower life cycle carbon footprint of about 4.4 $gCO_{2\text{-eq}}$/MJ compared to 93–110 $CO_{2\text{-eq}}$/MJ for methanol from natural gas and nearly 300 $gCO_{2\text{-eq}}$/MJ for methanol from coal. The life cycle carbon footprint of eMethanol is lower than that of methanol produced from renewable sources such as biomethane, solid biomass and renewable energy, which is between 10–40 $gCO_{2\text{-eq}}$/MJ.

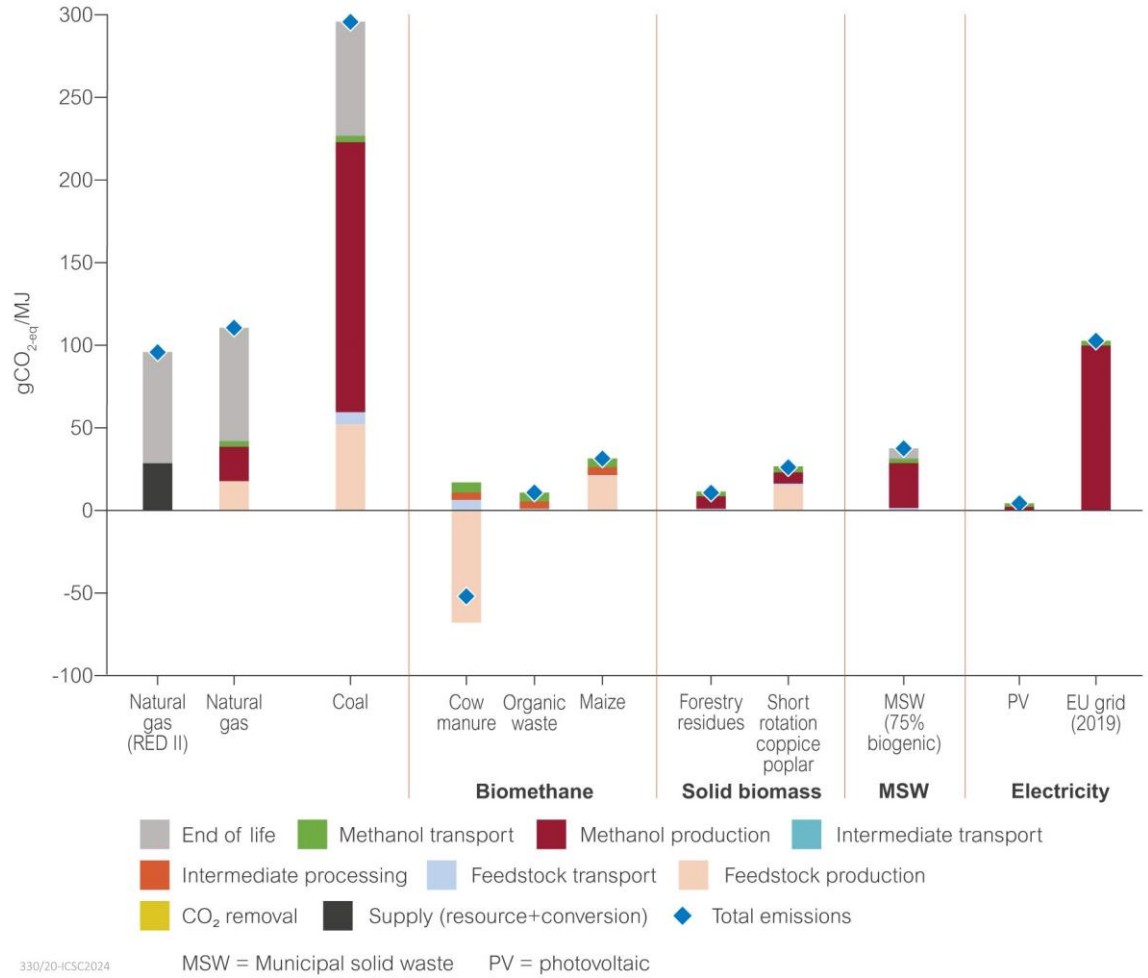

Figure 20 Life cycle carbon footprint of methanol pathways (Hamelinck and Bunse, 2022)

Similar findings were published by Jung and others (2022) who conducted a LCA of eMethanol as a marine fuel produced by the Liquid Wind's FlagshipONE project (described in Section 4.1.2). They assumed that:

- the production is powered by 100% wind electricity with a carbon intensity of 6.5 $gCO_{2\text{-eq}}$/kWh;
- steam is generated by biomass-fired combined heat and power plant;
- there is a negative carbon credit for capturing CO_2;
- process heat is recovered and fed into the district heating network, and is credited with negative emissions; and
- embodied emissions of technology and construction are negligible.

Their results show that the life cycle emissions of FlagshipONE eMethanol is about 5 $gCO_{2\text{-eq}}/MJ$. Replacing low-sulphur fuel oil with FlagshipONE eMethanol as a marine fuel could result in a reduction in life cycle carbon emissions of 94% (*see* Figure 21).

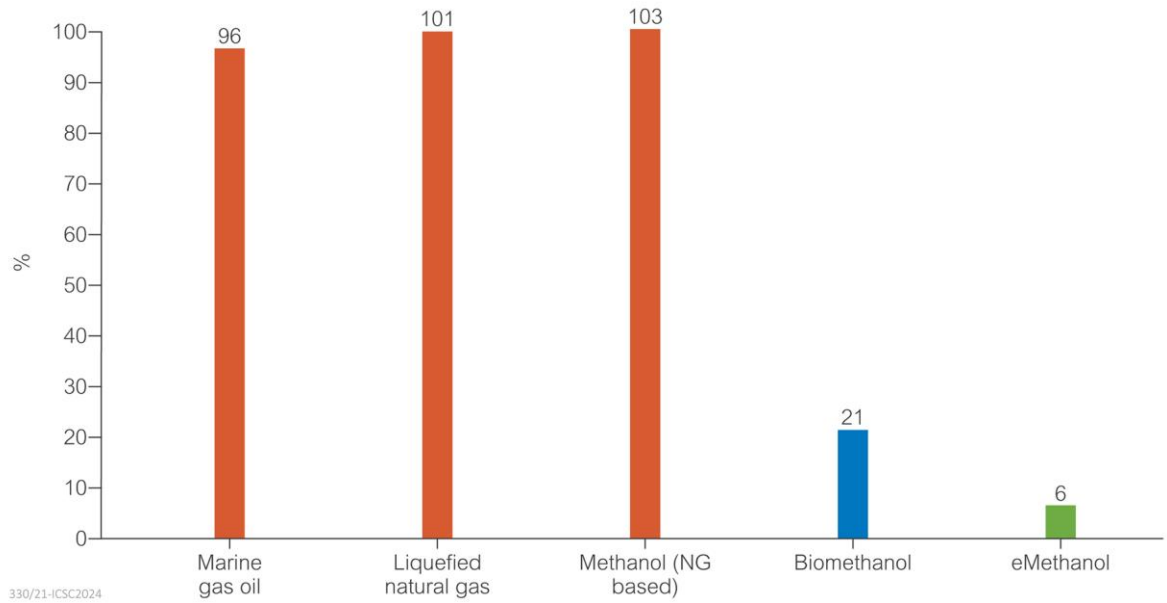

Figure 21 Life cycle carbon emissions of marine fuels compared to low sulphur fuel oil (100%) (Jung and others, 2022)

In the aforementioned study commissioned by Concawe and Aramco (Section 4.1.3), life cycle emissions of various e-fuels produced in different regions were evaluated and compared with fossil-fuelled counterparts. The results show that for all the e-fuels analysed, a significant reduction in GHG emissions can be attained relative to their fossil alternatives (Concawe and Aramco, 2022). Figure 22 compares the life cycle GHG emissions of various e-fuels produced in Northern Europe in 2050 with their fossil fuel counterparts.

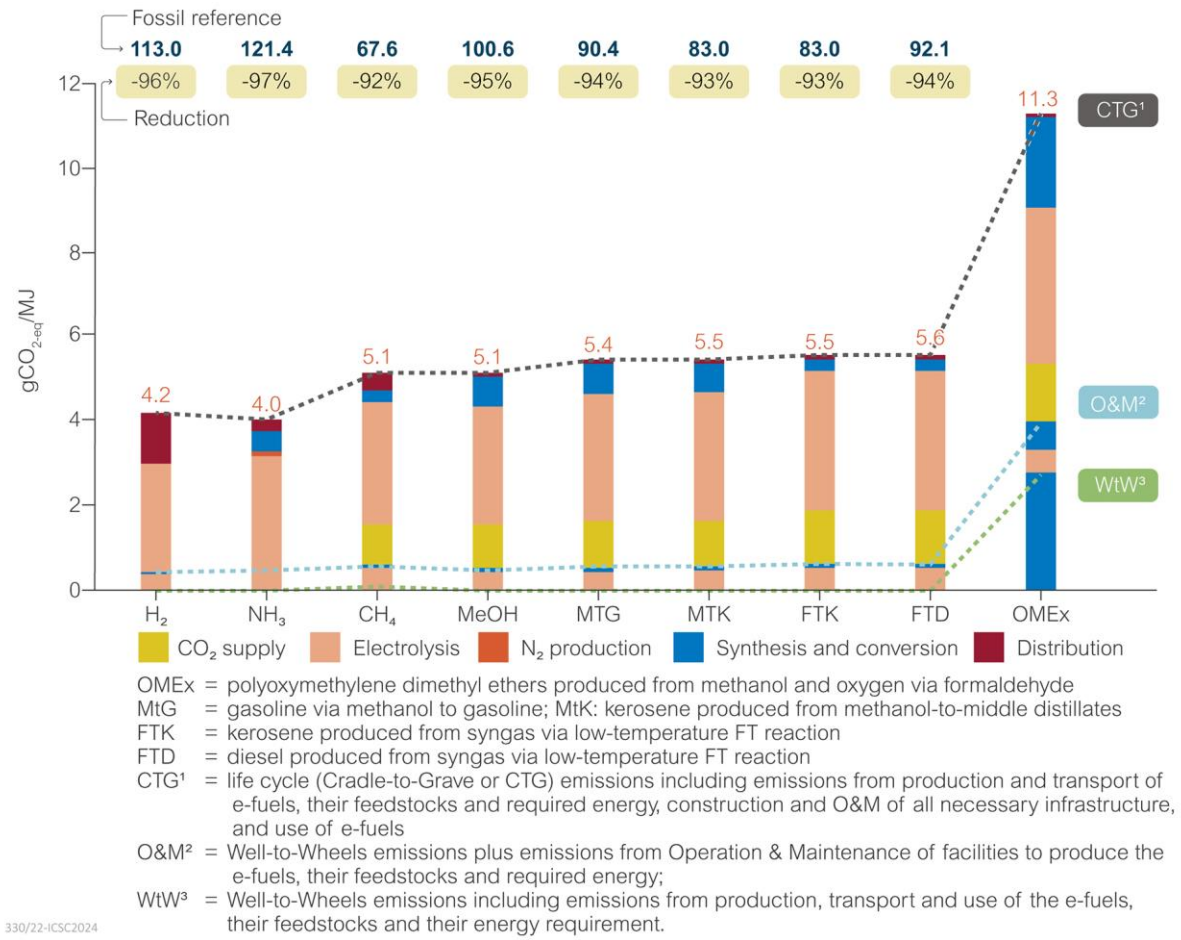

Figure 22 Life cycle GHG emissions of various e-fuels and their fossil fuel counterparts (Concawe and Aramco, 2022)

Several other studies (IEAGHG, 2021b; Prussi and others, 2020) indicate the carbon mitigation potential of e-fuels. Similar findings are also obtained for CO_2-derived chemicals and polymers. For the production of polyols with 20 wt% CO_2, life-cycle carbon emissions reductions of 11–19% relative to the conventional production process from fossil-based feedstock have been reported (Zhu, 2018; IEA, 2019).

Concrete and cement are among the most widely manufactured materials with around 30 Gt/y of concrete and 4.2 Gt/y of cement produced globally (IEA, 2019). The cement industry is responsible for approximately 7% of anthropogenic CO_2 emissions. CO_2 curing can lower the input of cement required to manufacture concrete. This reduces the upstream emissions related to cement production and is the major contributor to lowering the life cycle emissions of CO_2-cured concrete relative to conventionally cured concrete. A net CO_2 emissions reduction of approximately 18 kg/m^3 concrete or a reduction in the CO_2 footprint of CO_2-cured concrete by around 80% has been reported (Zhu, 2018; IEA, 2019). A major benefit of CO_2-cured concrete is the permanent retention of the carbon in the product.

Similarly, the permanent storage of CO_2 in building materials from the CO_2 mineralisation of wastes contributes to their low life-cycle emissions compared to conventionally produced aggregates. According to Carbon8 (2023), its ACT process fixes more CO_2 in the aggregate than it emits over its life cycle, resulting in a carbon-negative aggregate on the market. Several estimates suggest that the amount of CO_2 that could technically be absorbed by waste streams is in the range of 100–1200 $MtCO_2/y$ (IEA,2019).

Unlike building materials, the CO_2 used for the production of fuels and chemicals is eventually released back into the atmosphere as the product is combusted or degrades at the end of its lifetime. Therefore, potential climate benefits will come from replacing conventionally produced fuels and chemicals that have a higher carbon footprint with CCU products with a lower carbon footprint. If renewable energy is used in hydrogen generation, CO_2 capture, purification and conversion processes, significant reductions in life cycle CO_2 emissions can be achieved when the CCU products are substituted for their fossil fuel counterparts.

The IEAGHG (2021c) conducted a case study of Japan to assess the potential contribution of CCU to achieving the nation's climate goals. The results indicate that if CO_2 emissions from coal power plants, waste-to-energy plants, iron and steel blast furnaces and high-purity sources in the chemicals sector across Japan are captured and used to manufacture polyols and polymers, recycled aggregates and as feedstock for the cultivation of algae in closed bioreactors, they could make a positive contribution to Japan's emissions reduction ambitions. Capturing and utilising 5 $MtCO_2/y$ in 2030 and 25 $MtCO_2/y$ in 2050 could lead to a net CO_2 emissions reduction of 5.4 $MtCO_2/$ by 2030 and 16.9 $MtCO_2/y$ by 2050 in Japan. The reductions represent 2% and 6.4% of Japan's estimated emissions mitigation efforts in 2030 and 2050, respectively. Improving efficiency and CCU performance could increase this to over 10% in 2050.

5.2.2 Role of CCU in achieving NZE

Decarbonisation is central to efforts to reach NZE. A clean energy transition, improved energy efficiency, electrification and hydrogen are part of the pathway to NZE. While renewable energy offers some cost-competitive opportunities for emissions reduction, electrification based on renewable energy is complex and not a one-size-fits-all solution. The emissions reduction required needs to be achieved through a combination of technologies, especially in sectors such as cement, steel, aluminium, petrochemicals, shipping, aviation, and heavy industry that are more difficult to decarbonise. These sectors are responsible for nearly half of global CO_2 emissions, highlighting the importance of finding solutions for these industries in their decarbonisation efforts. CCUS solutions represent a promising path forward for these sectors (Kelsall, 2023).

CCUS has an important role in decarbonisation, particularly in hard-to-abate sectors. In aviation, for example, one of the hardest sectors to decarbonise, SAF can be produced by combining captured CO_2 and hydrogen using renewable energy. SAF have significantly lower carbon footprints than

conventionally produced aviation fuels. Substituting conventional aviation fuels with SAF can lead to a substantial decrease in total CO_2 emissions from aviation.

As CO_2 conversion can displace fossil fuel use and allows for the use of renewable electricity in the conversion processes, CCU can contribute to emissions reductions as part of a portfolio of clean energy technologies. CCU may also promote the deployment of renewable energy by offering co-benefits of energy storage.

From an economic standpoint, CCU is a better alternative than CCS because the products can generate an important revenue stream to offset whole or part of carbon removal costs and reduce the exposure of industries to increasing carbon prices. Therefore, CCU can provide a low-cost decarbonisation solution in some sectors and/or regions.

CCU could contribute to climate change mitigation by displacing an equivalent product with higher life-cycle CO_2 emissions such as fossil-based fuels, chemicals or conventional building materials. Although some CCU products only store the captured CO_2 temporarily and it is re-emitted back into the atmosphere when the product is used or disposed of, CCU captures and recycles the CO_2 and thereby reduces the use of fossil fuels and their related emissions.

CCUS can act as a bridging technology in the energy transition. CCU can play a limited but vital role as part of the portfolio of technologies and measures needed to achieve global energy and climate change mitigation goals.

5.2.3 CCU in a circular economy

As well as an energy source, fossil fuels have provided carbon for the manufacturing of many important products. CO_2 is one of a few alternative sources of carbon. Even in a NZE economy, carbon will still be required in several applications. Also, there will be some unavoidable emissions in the foreseeable future such as CO_2 emissions from aviation, shipping, fossil fuel-fired power plants and some bioprocesses. Carbon cycling can help to close the carbon loop and create a circular economy.

CCU technologies enable the use of biogenic CO_2, CO_2 from fossil energy and industrial sources or DAC for the production of fuels, chemicals and building materials to deliver climate benefits. In addition to being a source of carbon, CO_2 use allows for the utilisation of renewable energy in hard-to-abate sectors such as transport and industry, thus limiting the use of fossil fuels. If each carbon molecule is used twice: for example, the CO_2 from fossil fuels use is captured, then used in combination with hydrogen to produce a fuel or chemical, and is eventually re-emitted back into the atmosphere, a maximum emissions reduction of 50% can be achieved from an energy system perspective (IEA, 2019). If biogenic CO_2 or CO_2 from DAC is used, the life cycle emissions can be minimised. In principle, carbon cycling via capturing and reusing the carbon content of various waste streams and products at

end of life can be repeated. Therefore, CCU can become part of a circular economy and a form of sustainable waste processing.

5.3 DRIVERS AND CHALLENGES

Climate change mitigation is the primary driver for the increased interest in CCU. This creates interest in CCUS for new business opportunities, technology leadership and energy security. Most countries have set NZE goals for the middle of this century or soon after, and several major companies have also established decarbonisation targets. Market uptake of CCU could be driven by a need to comply with targets or regulations. Some CCU products such as CO_2-derived building materials and polymers already have a business case in certain regions, without additional policy or regulatory support. CCU appeals to industry, especially the hard-to-abate sectors because it provides versatile and practical solutions for emissions reduction and supports a circular economy. CCU does not only decarbonise these sectors, but it also offers increased sector integration and provides flexibility and security of supply at the same time. CCU products can serve as a low-carbon alternative to replace fossil-based fuels, chemicals and other conventionally produced equivalents in today's markets. Therefore, CCU can represent significant business opportunities for CO_2-based products and related technologies. In addition, CCU creates value through CO_2-based products while avoiding the storage costs and concerns of geological storage of captured CO_2, making CCU attractive to some producers and technology providers. A select few CCU pathways are driven by cost-savings or better performance of products. Another driver is the funding and investment incentives provided by governments, such as the Innovation Fund in the EU and the IRA in the USA, which have spurred the development of several large CCU projects. However, greater government support is required for economy-wide deployment of CCU.

The biggest barrier to the widespread uptake of some of the CCU technologies is cost. However, a few routes such as CO_2-based polymers and building materials, are driven by cost-savings or improvements to the value of products. There are no significant barriers to polymer production although some non-identical products need to be tested, validated and approved for their suitability for specific end-uses. For building materials, the production of waste-to-aggregates may be limited by the availability and access to waste residues and regulatory approval for final products. CCU routes for chemicals and fuels, particularly the renewable hydrogen pathways, are energy-intensive and have high capital and operating costs. The high energy demands and limited availability of hydrogen may also become obstacles that limit large-scale CCU deployment. In addition, there is a lack of infrastructure for the storage and transport of hydrogen and/or CO_2. Deployment of CCU at a competitive market scale would require significant increases in both hydrogen production capacity and low-emission electricity generation capacity and the development of distribution and storage infrastructure. Establishing supportive policies and upgrading some of the existing regulations and product standards are also required.

5.4 COMMENTS

Early markets are emerging, but the future scale of CO_2 use is uncertain. Nevertheless, CO_2-derived fuels show the greatest potential scale for deployment followed by building materials and chemicals owing to their existing market size. There is greater political and regulatory support for sustainable e-fuels, with some regions, such as the EU, introducing mandates or standards for their use. This could increase the uptake of e-fuels, provided the benefits of synthetic CCU fuels are recognised within the regulations.

In most cases, CO_2-based fuels and chemicals are considerably more expensive than their fossil-based equivalent. CO_2-derived polymers could be produced at a lower cost than their fossil counterparts, but the market is relatively small. CO_2-based building materials can be competitive today and have bigger potential under existing market drivers. CO_2-based building materials show greater environmental benefits than other CCU products as they can lock up CO_2 permanently.

For CO_2 conversion routes that are not cost-competitive with conventional fossil-based production, external drivers such as carbon pricing or product mandates and incentives or subsidies are required to encourage uptake. Taking SAF as an example, the EU's 'Fit for 55' package released in 2021 included a draft ReFuel Regulation (EC, 2023). The proposed law stipulates that, from 2025, all flights departing from EU airports should have a minimum share of 2% SAF. That percentage will rise to 6% in 2030, and to 70% by 2050. This new law has prompted the development of several commercial CO_2-to-fuel projects in Europe as discussed in Section 4.1. All these projects have received funding and financial support from the EU and/or local government or are applying for it. The fact that most of the global CO_2-to-fuel projects are being developed in Europe highlights the importance of appropriate regulations and policies for the commercial-scale deployment of SAF. However, because of the high cost of SAF, a financing mechanism and incentives and other supporting policies are also needed. The EU is considering tax credits similar to the USA's IRA for investors and developers.

Almost all the CCU pathways considered exhibit potential for lower life cycle emissions per tonne of product compared to conventionally produced counterparts. CCU can provide climate benefits where the application is scalable, uses low-emission energy, and displaces a product with higher life-cycle emissions. CCU offers versatile and practical solutions for emissions reduction in hard-to-abate sectors, so it can be used as a supplement to other technologies and measures and play an important role in efforts to achieve NZE and a circular economy. The barriers to near-term scale-up of CCU are commercial (high cost and lack of required infrastructure) and regulatory rather than technological.

Despite significant potential, the growth in demand for CO_2 is restricted by the anticipated market demand for CCU products. The estimated future CO_2 demand from the application of the selected CCU technologies is modest. In the IEA's scenario analysis with limited deployment of CO_2 storage, CO_2 use will increase within the energy system including for e-fuels production but delivers less than 13% of

the emissions reductions that would otherwise be provided from CO_2 storage (IEA, 2019). Therefore, CCU is not expected to deliver emissions reductions on the same scale as other options such as CCS. Rather, as a complement, CCU can play a critical role as part of an 'all technologies' approach in meeting global energy and climate goals.

6 CONCLUSIONS

Many countries have NZE emission targets ranging from 2050 to 2070, with a reduction of CO_2 emissions of around 40% by 2030. CCUS is increasingly recognised for its potential role in carbon emissions mitigation and in a circular NZE economy. A growing number of countries include CCUS technologies in their long-term climate change mitigation policies, led by North America and Europe which host the most robust climate and CCUS policy mechanisms including significant funding and investment incentives. Climate change and CCUS policies are also advancing in the Asia-Pacific region and are being considered in other countries.

After years of slow progress and insufficient finance, the recent investment incentives and climate targets are building momentum behind CCUS, which is growing rapidly. More projects, policies, and funding have been announced globally in America, Asia Pacific, Europe and the Middle East this decade. However, despite the recent significant increase in scale and deployment worldwide, CCUS is still in the early stage of technology and market development.

CCUS covers a wide variety of technologies and processes with varying levels of technical and commercial maturity, and differing mitigation potential across a range of applications. The operation of several large-scale demonstration plants has proven that combining a CCU facility with coal-fired power plants for low-carbon electricity production is technically feasible and can also be economically viable under the right conditions.

A matrix of conversion technologies to produce commercially established products has reached the demonstration or commercialisation stage. It shows the potential applicability of different technologies to various industries or processes. New conversion technologies using various routes are under development. Technologies for CO_2-cured concrete, waste-to-aggregates, methanol, and polycarbonates are ready for commercial deployment with several industrial-scale plants already built and operational, and other projects under development.

Almost all the CCU pathways considered exhibit potential for lower life cycle emissions compared to conventionally produced counterparts. CCU can provide climate benefits where the application is scalable, uses low-emission energy, and displaces a product with higher life-cycle emissions. The opportunities for CCU are vast, with potential applications spanning various sectors from gas and liquid natural gas processing, production of hydrogen, chemicals and synthetic fuels, renewable energy integration, power generation and distribution, and more.

This means that CCU can create a demand for captured CO_2 as a feedstock. Early markets are emerging. Although future commercial development will be variable and market interest uncertain, CO_2-derived fuels present the greatest potential scale for deployment followed by building materials and chemicals owing to their market sizes. The uptake of e-fuels will be higher in regions such as the EU and USA

where there is greater political and regulatory support for these products. However, even if the full market potential is met, the scale of carbon emissions reductions that can be achieved by CCU is limited. Thus, CCU cannot deliver emission reductions on the same scale as other options such as CCS. Rather, CCU can complement other measures as part of an 'all technologies' approach to meeting global energy and climate goals.

In most cases, CO_2-based fuels and chemicals are more expensive than their fossil-based equivalent, which is the biggest obstacle to their widespread deployment. CO_2-derived polymers could be produced at a lower cost than their fossil counterparts, but they have limited emissions mitigation potential due to the relatively small market size. CO_2-based building materials can already be competitive and have larger potential under existing market drivers. CO_2-based building materials show greater environmental benefits than most other CCU products as they can lock up CO_2 on a more permanent basis. In general, barriers to the near-term scale-up of CCU are commercial and regulatory rather than technological.

CCU can displace an equivalent product with higher life-cycle CO_2 emissions such as fossil-based fuels, chemicals or conventional building materials. It offers versatile and practical solutions for emissions reduction in hard-to-abate sectors where alternatives are technically limited, contributing to emissions reductions as part of a portfolio of clean energy technologies. Therefore, CCU has the potential to help decarbonise power, transport and other industrial sectors and generate revenue through marketable products.

Finally, CCU can provide a new source of essential carbon feedstock in the transition from fossil resources, and so help to close the carbon loop and create a circular economy, an important goal for the future.

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