Evaluating technology options to mitigate greenhouse gas emissions

Greenhouse Gas Emissions Accounting for CO_2 Capture and Utilisation (CCU) Technologies

Characterising CCU Technologies, Policy Support, Regulation and Emissions Accounting

IEAGHG Technical Review
2018-TR01a
March 2018

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- 2018-TR01a "Characterising CCU technologies, policy support, regulation and emissions accounting"
- 2018-TR01b "Greenhouse gas accounting guidelines for CCU"
- 2018-TR01c "Synthesis of research findings"

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IEA Greenhouse Gas R&D Programme

Greenhouse Gas Emissions Accounting for Carbon Dioxide Capture and Utilisation (CCU) Technologies

Characterising CCU technologies, policy support, regulation and emissions accounting

FINAL REPORT

Carbon Counts Company (UK) Ltd

20 March 2017 (with updates to February 2018)

Prepared by:
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Our Ref: 083

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Acronyms and Abbreviations

ACR	American Carbon Registry
AFP	Alternative Fuel Portal
AM	Approved Methodology (CDM)
ANL	Argonne National Laboratory
ARB	California Air Resources Board
ARRA	American Recovery and Reinvestment Act
BOCM	Bilateral Offset Crediting Mechanism
BMBF	Federal Ministry of Education and Research (Germany; BMBF in German)
CCS	Carbon dioxide (CO_2) capture and storage
CCU	CO_2 capture and utilisation
CDM	Clean Development Mechanism
CDM M&Ps	CDM modalities and procedures
CER	Certified Emission Reduction
CH_4	Methane
CNG	Compressed Natural Gas
CO	Carbon monoxide
CO_2	Carbon dioxide
CRI	Carbon Recycling International
DME	Dimethyl ether
DOE	United States Department of Energy
EC	European Commission
EOR	Enhanced Oil Recovery
EPA	Environmental Protection Agency
EU	European Union
FQD	Fuel Quality Directive
GHG	Greenhouse Gas
GREET	Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation
Gt	Gigatonne
ICEF	Innovation for Cool Earth Forum
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
IPCC	Intergovernmental Panel on Climate Change

ISCC	International Sustainability & Carbon Certification
ISO	International Organization for Standardization
JCM	Joint Crediting Mechanism
LCA	Life-cycle assessment
LCFS	Low carbon fuel standard
LPG	Liquefied petroleum gas
METI	Ministry of Economy, Trade and Industry
MJ	Megajoule
MRV	Measurement, Reporting and Verification
MTO	Methanol-to-olefins
NDC	Nationally Determined Contribution
NETL	United States National Energy Technology Laboratory
R&D	Research and development
REC	Renewable Energy Certificate
RED	Renewable Energy Directive
RFNBO	Renewable Fuel of Non-Biological Origin
RFS	Renewable Fuel Standard
RIN	Renewable Identification Number
RTFO	Renewable Transport Fuel Obligation
RVO	Renewable Volume Obligations
SCOT	"Smart CO2 Transformation" programme
SET-Plan	European Union Strategic Energy Technology Plan
SNG	Synthetic Natural Gas
SRCCS	Special Report on Carbon Dioxide Capture and Storage (IPCC)
t	Tonne
TRL	Technological Readiness Level
UNFCCC	United Nations Framework Convention on Climate Change
VCS	Verified Carbon Standard
VOC	Volatile Organic Compounds
WEF	World Economic Forum

EXECUTIVE SUMMARY

The report has been prepared by Carbon Counts Company (UK) Ltd ("Carbon Counts") for the IEA Greenhouse Gas R&D Programme ("IEAGHG") under the assignment "Greenhouse Gas Emission Accounting for Carbon Dioxide Capture and Utilisation Technologies".

The overall aim of the study is to gain a better understanding of the potential of carbon dioxide (CO_2) capture and utilisation (CCU) technologies[1] to contribute towards climate change mitigation objectives (i.e. by reducing emissions of anthropogenic CO_2 to the atmosphere). This Activity 1 report provides a rapid assessment of the historical development (since around the mid 2000s) and current status of CCU technology across many parts of the world. The results allow for a number of generalised conclusions to be drawn regarding the current technological, political and regulatory environment in which CCU technologies are developing today.

Looking back 12 years from today, CCU technology was largely on the fringes of mainstream climate change mitigation science. For example, in 2005 the Intergovernmental Panel on Climate Change (IPCC) in its *Special Report on Carbon Dioxide Capture and Storage* (SRCCS; Metz *et al*. 2005) concluded that '*the contribution of industrial uses of captured CO_2 to climate change mitigation is expected to be small*'.[2] To an extent this view persists today: in its latest considerations, the IPCC's Fifth Assessment Report (AR5) (Fischedick *et al.*, 2014) also concluded – in reference to the SRCCS – that '*industrial uses of CO_2 are unlikely to contribute to a great extent to climate change mitigation*'. These views notwithstanding, it is increasingly apparent that political and academic momentum behind CCU has increased significantly over recent years.

To an extent, the growing interest has been spurred by the apparent failure of CO_2 capture and storage (CCS) to materialise as a cost-effective and scalable mitigation technology in many parts of the world so far, despite previously anticipated breakthroughs. But the debate is wider than that. Alongside greenhouse gas (GHG) emission reductions, CCU offers other drivers for its consideration, such as benefits of resource efficiency, resource depletion and resource security (Zimmerman and Kant, 2015) – primarily through substitution of virgin raw materials, particularly crude oil for chemicals and fuel production – and industrial innovation through the conversion of waste to valuable product, encapsulated within the 'circular economy' concept.

The growing political momentum has manifested itself firstly in the establishment of a number of reasonably large government research and development (R&D) funding programmes for CCU technology since about 2009. This includes the 2009 American Recovery and Reinvestment Act (ARRA) in the United States (US), and the Federal Ministry of Education and Research (BMBF) programme in Germany. These collectively exceeded US$200 million in grant support for at least 50 such activities. Other smaller-scale support has also been offered by the European Commission and the governments of the United Kingdom (UK) and France. These efforts notwithstanding, uncertainty remains regarding the true potential of CCU technologies to deliver real, measurable, verifiable and scalable GHG emission reductions. This is largely due to a lack of

[1] The term CCU covers a range of technologies, typically classified as CO_2 to chemicals, CO_2 to fuels and CO_2 for mineralisation. These are discussed in more detail in later sections of this report.
[2] Technical Summary, p. 41

transparency by operators regarding the energy and carbon balances of CCU processes, resulting in a significant asymmetry in understanding between policy-makers and developers.

This lack of understanding has in part also prompted a second approach to promoting CCU technologies: the use of inducement prizes and Grand Challenges in the US, Canada and Europe (e.g. the *Carbon XPrize* in the US and the European Commission's *CO_2 Reuse Prize*). These types of support measures can be employed alongside R&D grant funding as a means to accelerate technology innovation by offering 'stretch' incentivises for researchers. Inducement prizes can work effectively where there are a number of competing technologies that can potentially deliver similar outcomes, and where there is a lack of transparency about the real potential of differing approaches to achieve significant, commercially-viable and scalable benefits. They can also help to reduce the asymmetry in knowledge between researchers and policy-makers as they usually require data and information to be collected and submitted in pursuit of the prize aim. Most of these programmes will conclude over the period 2019-2021, after which greater knowledge should be forthcoming regarding the potential of CCU technologies and their ability to reduce GHG emissions.

Notwithstanding the ongoing asymmetry of information and its potential resolution in the next few years through the prize programmes, the political momentum behind CCU technologies seems to be continuing unabated. Many of these efforts are focussed on bringing CCU technologies into the ambit of mainstream climate change mitigation policies, particularly alongside CCS. Presently, CCU technologies are largely excluded from such schemes, primarily due to concerns over GHG accounting and measurement, reporting and verification (MRV) in respect of the net GHG benefits they might deliver, and issues of boundary setting, emissions leakage and permanence in the accounting/MRV rules. For example, actions in Europe are seeking to include CCU within the EU's emission trading scheme (ETS) and the Renewable Energy Directive (RED) supplier obligation for low carbon transport fuels within the next two to three years. Likewise, in the US some CO_2-based algal fuel producers have been accredited under the Federal Renewable Fuel Standard, and proposals have been made to include CCU in the 45Q Sequestration Tax Credit scheme – now embodied in the proposed "FUTURE Act". The FUTURE Act – originally put forward in July 2016 as the Carbon Capture Utilization and Storage Act – is receiving bi-partisan support from 25 senators in the Upper House. As well as extending the scope of the tax credit to various forms of CCU (not just enhanced oil recovery using CO_2), it includes provisions to increase the level of tax credit from US$5 to 10 per tonne sequestered to an amount increasing linearly over 12 years from around US$12-22 up to US$50 per tonne. In addition, the US Environmental Protection Agency's (EPA) Clean Power Plan also makes provision for CCU inclusion within the scheme.

These activities are seemingly backed up by influential corporate and academic groups such as the *World Economic Forum*, which is supporting the *Global CO_2 Initiative*, a group seeking to realise *'the ambitious goal of capturing 10% of global CO_2 emissions and transforming them into valuable products'* (Global CO_2 Initiative, 2016). This is also being backed by leading international experts such as David Sandalow, Inaugural Fellow at Columbia University's Center on Global Energy Policy, former Under Secretary of Energy (acting) and Assistant Secretary for Policy & International Affairs at the US Department of Energy (DOE), and Steering Committee member of the Innovation for Cool Earth Forum (ICEF). David Sandalow was a lead author of the ICEF CCU

Roadmap that provided the ambitious estimate that the main product groups involved in CCU could utilise around 7 $GtCO_2$/year and create a market of over US$800 billion by 2030 (Global CO_2 Initiative/ICEF, 2016). In all cases, however, regulators have provided clear signals that inclusion is subject to resolving the GHG accounting and MRV uncertainties and challenges outlined above.

The actions at a political level and the R&D activities for CCU on the ground appear to be out of synchronisation. The number of commercial CCU project developments around the world today are limited, are often only viable in unique niche circumstances, and most are at technology readiness level (TRL) 5 or less. Realistically, it seems reasonable to conclude that these technologies can only be considered as mainstream climate mitigation tools if proven over the next 5-10 years. Moreover, there is genuine uncertainty about whether CCU technologies do actually deliver net GHG emission reductions, and whether they can be scaled-up to create deep cuts in global GHG emissions over the medium term. These uncertainties are manifested in forthcoming challenges that will be faced by regulators in trying to ensure that GHG emission reduction policies into which CCU is trying to be 'mainstreamed' include sufficiently robust GHG accounting and MRV rules. These are necessary to ensure that emission reductions achieved by CCU, and the associated revenues, are effectively tracked and calculated according to the net GHG benefit delivered rather than claimed. Whilst there is undoubtedly strong low-carbon potential across the pool of emerging CCU technologies, the challenge will lie in appropriately promoting and rewarding the most viable and effective ones.

As such, the work programme envisaged within this project will provide a timely addition to the knowledge base and a useful intervention in the ongoing political debates taking place around CCU. It should help regulators to gain a clearer picture of the issues associated with GHG accounting and MRV for CCU technologies, and help them shape rules, regulations and guidelines accordingly.

BACKGROUND

The report has been prepared by Carbon Counts Company (UK) Ltd ("Carbon Counts") for the IEA Greenhouse Gas R&D Programme (IEAGHG). The report covers Activity 1 of the assignment "Greenhouse Gas Emission Accounting for Carbon Dioxide Capture and Utilisation Technologies" being implemented by the IEAGHG.

PURPOSE AND SCOPE

The overall aim of the study is to gain a better understanding of the potential of carbon dioxide (CO_2) capture and utilisation (CCU) technologies[1] to contribute towards climate change mitigation objectives (i.e. by reducing emissions of anthropogenic CO_2 to the atmosphere). This will be achieved through a multi-staged study covering the following:

Activity 1 – Characterising CCU technologies and emission reduction pathways
Activity 2 – CCU facility-level GHG emissions
Activity 3 – Developing a composite life-cycle GHG emission profile for CCU activities
Activity 4 – Assessing GHG accounting options

The focus of this report is on Activity 1 – the characterisation of CCU technologies and an assessment of their potential to contribute towards climate change mitigation goals. It draws upon published literature on the subject and views and opinions expressed by various stakeholders.

Over recent years, interest in CCU from policy-makers, industry and academics has increased dramatically, although uncertainty remains regarding the technology's true potential to contribute towards wider greenhouse gas (GHG) emissions reduction goals. A range of views have been expressed in these contexts, but on the whole it remains largely speculative and unproven at the time of writing. Consequently, it is difficult to provide firm opinions on whether CCU technologies can make a meaningful and lasting contribution to tackling climate change. In this report, **Part 1** provides an assessment of the range of views presented by various stakeholders, and attempts to establish an empirical evidence base upon which to qualify the views and opinions expressed.

Additionally, the key way to gain a clearer understanding of the potential for CCU technologies to reduce GHG emissions is to assess the overall energy and carbon balances for different CCU processes, and to take a view on how and whether these could make a contribution to GHG emission reductions. In other words, as noted by the Intergovernmental Panel on Climate Change (IPCC) in its 2005 Special Report on Carbon Dioxide Capture and Storage (SRCCS; Metz *et al.*, 2005): *'further study of the net energy and CO_2 balance of industrial processes that use the captured CO_2 could help to establish a more complete picture of the potential of this option'*.[2] To the best of our knowledge, such detailed studies have, at best, only partially been carried out (or at least disclosed in the public domain e.g. Global CCS Institute, 2011) and are heavily reliant on

[1] The term CCU covers a range of technologies, typically classified as CO_2 to chemicals, CO_2 to fuels and CO_2 for mineralisation. These are discussed in more detail in later sections of this report.
[2] Technical Summary, p. 48

the assumptions made in the analysis. Therefore, subsequent parts of this study (under Activities 2 and 3) will involve the development of case studies of different operational CCU facilities to assess this potential.

Prior to making this assessment, it is important to understand the types of GHG emission accounting that can be applied to make such an assessment. To address this question, **Part 2** of this report provides a review of various GHG accounting rules and measurement, reporting and verification (MRV) guidelines in terms of how they treat CCU technologies – or otherwise exclude them – at the current time. Building on this review – and the case studies developed – potential approaches for accounting for the GHG emissions effects of CCU technologies will be developed under Activity 4.

PART 1: CHARACTERISING CCU TECHNOLOGIES

1 SETTING THE SCENE

As highlighted above, interest has been growing over recent years regarding the role of CCU in mitigating GHG emissions. Looking back 12 years from today, the technology was largely on the fringes of mainstream climate change mitigation science. For example, in 2005 the IPCC SRCCS (Metz, *et al*. 2005) concluded that '*the contribution of industrial uses of captured CO_2 to climate change mitigation is expected to be small*'.[1] To an extent this view persists today: in its latest considerations, the IPCC's Fifth Assessment Report (AR5) (Fischedick *et al.*, 2014) also concluded – in reference to the SRCCS – that '*industrial uses of CO_2 are unlikely to contribute to a great extent to climate change mitigation*'. Similarly, the United States (US) government, through the Department of Energy (DOE) National Energy Technology Laboratory (NETL) also presently takes the view that *'CO_2 utilization will not be effective as a tool to mitigate GHG emissions by itself'* but is rather *'a promising research area…that can potentially provide economic benefits for fossil fuel-fired power plants or industrial processes'* (National Energy Technology Laboratory, 2014).

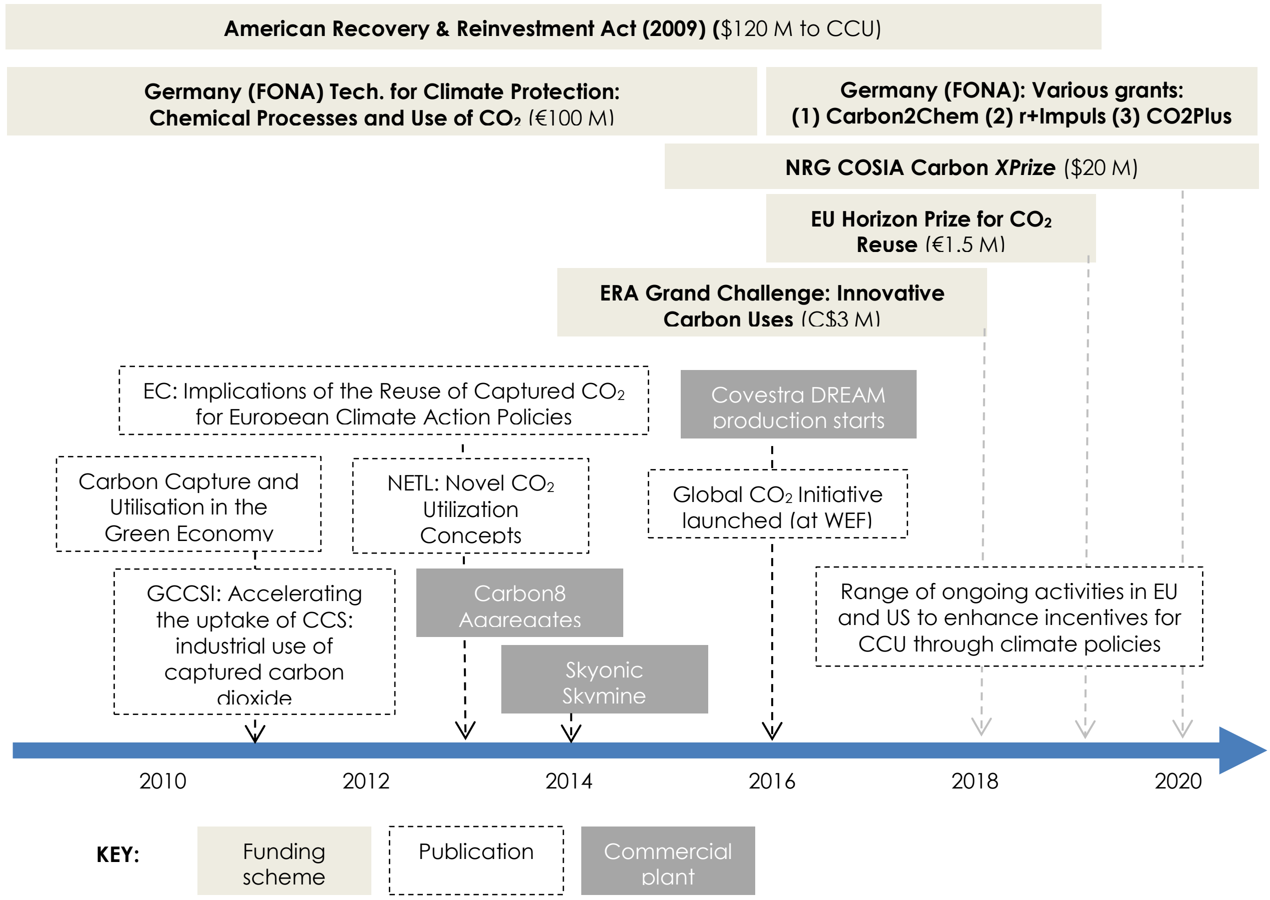
The IPCC and DOE views notwithstanding, it is apparent that perceptions about CCU have changed somewhat over the last 10 years or so. Today, a range of activities can be identified that indicate increasing political and academic efforts to promote the emissions reduction potential of CCU. Some of the notable milestones over this period include:

- Establishment of multi-million dollar/euro (US$/€), multi-year, grant funding programmes in the US[2] and Germany[3], since 2009;
- Various smaller-scale national research programmes covering subjects relating to CCU in the United Kingdom, France and Italy;
- The launch of Grand Challenges and innovation prizes in Canada, the US and Europe in 2014, 2015 and 2016 respectively;
- Publication of various seminal reports describing the potential of CCU in support of climate mitigation objectives;
- The launch, at the start of 2016, of the *Global CO_2 Initiative* with the aim of catalysing innovative research in CCU and accelerating commercialisation of CCU products in order to realise *'the ambitious goal of capturing 10% of global CO_2 emissions and transforming them into valuable products'* (Global CO_2 Initiative, 2016);
- A range of ongoing political efforts to increase the profile and recognition of CCU technologies within GHG reduction policies in both the US and Europe.

These developments are highlighted schematically below (Figure 1.1), and described in greater detail in Section 3.

[1] Technical Summary, p. 41
[2] American Recovery and Reinvestment Act (ARRA) funding of around US$120 million (M)
[3] Federal Ministry of Education and Research (BMBF), Research for Sustainability (FONA) funding of around €100 M on "Technologies for Sustainability and Climate Protection – Chemical Processes and Use of CO_2"

Figure 1.1 Recent and ongoing milestones for CCU development (2009-2020)



A similarly large growth in academic work can also be seen over the same period, as indicated by the level of journal citations involving the topic of CCU (Zimmerman and Kant, 2015). Data from Thomson Reuter's *Web of Science* regarding the number of articles containing the key words 'CO_2' and 'utilisation'[1] and the level of citations of such articles shows that the trend over recent years has been upwards and exponential (Figure 1.2).

To an extent, this growing interest has been spurred on as a response to the apparent failure of CO_2 capture and storage (CCS) to materialise as a cost-effective and scalable mitigation technology in many parts of the world so far, despite previously anticipated breakthroughs. To put this into context, during the 2000s the G8, the European Union (EU), the International Energy Agency (IEA) and the IPCC and all set out ambitious visions for CCS deployment through the first part of the 21st century, including the following:

- The construction and operation, by 2015, of up to 12 demonstration plants of sustainable fossil fuel technologies (i.e. CCS) in commercial power generation in Europe (Council of Ministers, 2007);
- Support the launching of 20 large-scale CCS demonstration projects globally by 2010, taking into account various national circumstances, with a view to beginning broad deployment of CCS by 2020 (G8, 2008);

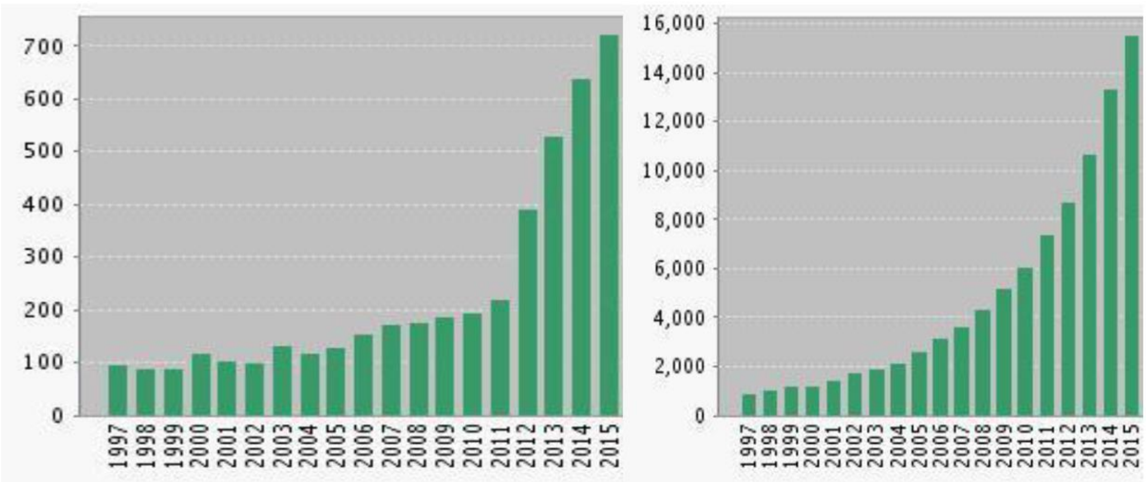
[1] In the title, abstract or text (excluding medical research)

- The construction and operation, by 2020, of around 100 CCS projects globally capturing around 100 $MtCO_2$/year (International Energy Agency, 2009);
- Potential for mitigation of around 800 $MtCO_2$ by 2030 (IPCC AR4; Barker *et al*., 2008).

Although progress with CCS is being made – including the completion and commissioning of the first plants fitted to coal-fired power plants (Boundary Dam, Saskatchewan, Canada; Petra-Nova, Houston, USA) and the world's biggest CCS project set to start injecting CO_2 in the first part of 2017 (Gorgon, Australia) – the fact that presently only 16 large-scale CCS projects[1] are in operation around the world today (Global CCS Institute, 2017) is indicative of significant technological, financial and political challenges to its potential.

Figure 1.2 Citation Report from Web of Science for 'CO_2' and 'Utilisation' (1997-2015)

(1) Number of articles *(2) Count of citations*



Source: Zimmerman and Kant, 2015 (based on data from Thompson Reuters *Web of Science*)

Such challenges have presented an opportunity for other approaches to industrial GHG emission mitigation to enter into the debate, in particular CCU. This is partly because it may act as an enabler for CCS by promoting CO_2 capture within industry. But on the other hand, CCU technologies are often positioned *against* CCS as an alternative approach that creates value rather than costs and liabilities (in the shape of CO_2 storage sites). This latter type of argument has proved attractive when considering some of the challenges facing CCS, such as financing and public perception. This situation is most apparent in Germany where CCS has largely been rejected by the public and mainstream media and CCU is now the core technology under consideration as a means to mitigate and utilise industrial CO_2 (Mennicken, 2016). To an extent, it could be argued that this attitude is starting to pervade thinking within the EU, where the Commission has made a number of attempts to get CCS off the ground without success (e.g. the use of funds from the European Energy Programme for Recovery (EEPR) and the 'NER300').

But the debate is wider than that. Alongside GHG emission reductions, CCU offers other drivers for its consideration, such as benefits of resource efficiency, resource depletion and resource security (Zimmerman and Kant, 2015) – primarily through substitution of virgin raw materials,

[1] Large-scale is defined as >1 $MtCO_2$/year

particularly crude oil for chemicals and fuel production – and industrial innovation through the conversion of waste to valuable product, encapsulated within the 'circular economy' concept.

In these contexts, the World Economic Forum (2014) identified CO_2 as a possible signature 'rough diamond' material for future innovations in the circular economy through CCU.[1] Similarly, although the EU considers the topic of CCU under the scope of the European Commission's *Strategic Energy Plan* (SET-Plan; European Commission, 2015a), its role in supporting the EU's *Circular Economy Action Plan* (European Commission, 2015b) is also widely referenced by Commission officials (e.g. European Commission, 2016c), and is also embodied in work around 'Key Enabling Technologies' (KETs) for industrial growth and innovation. In Japan, the circular economy concept has been in existence for many years, as embodied in the 2000 *Basic Act on Establishing a Sound Material-Cycle Society*, and encoded into the 2000 *Law for the Promotion of Efficient Utilization of Resources*; CCU could be a major contributor to new innovations in sound material cycle management, and also complement other initiatives such as the Ministry of Economy, Trade and Industry's (METI) artificial photosynthesis research programmes.

The backdrop described highlights the scale and growth of interest in CCU technologies over recent years. At the time of writing, it is apparent that whilst there is pressure to move ahead with mainstreaming CCU technologies into broader climate policies, and in particular incentive mechanisms , serious questions remain over its efficacy as an emission reduction technology. As such, this study offers a timely intervention into the debate, and should prove useful in helping inform key policy decisions scheduled for the next few years.

Against this backdrop, the remaining sections of Part 1 of the report present:

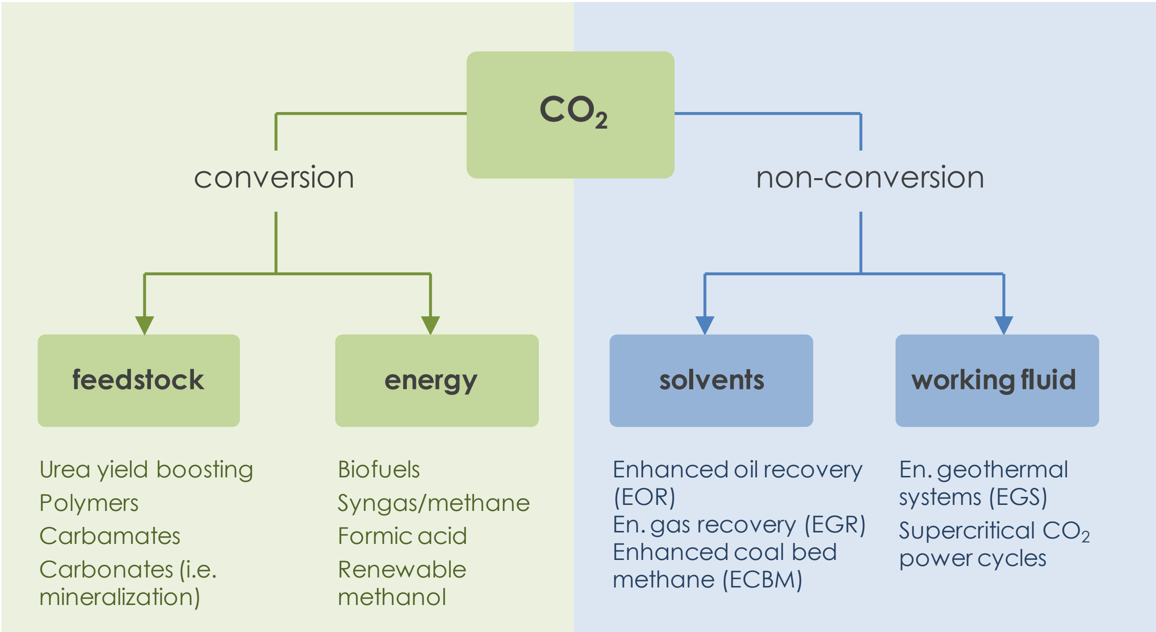
- The front-running technologies considered under the umbrella of 'CCU' (Section 2);
- The activities ongoing around the world to support their development and implementation (Section 3); and,
- The potential such technologies could offer for GHG emission reductions (Section 4).

[1] A rough diamond is defined by WEF as 'large-volume by-products of many manufacturing processes, such as CO_2 and food waste…that could provide additional value and displace virgin materials intake.'

2 ABOUT CCU TECHNOLOGIES

The term 'CO_2 utilisation' refers to a wide range of technologies that can either use CO_2 in its pure form as a working fluid or solvent without conversion (sometimes referred to as 'direct use') or as a feedstock for conversion into other value-added products (Figure 2.1).

Figure 2.1 Simple classification of emerging CCU technologies



Source. Modified from: European Commission, 2013. *Implications of the Reuse of Captured CO_2 for European Climate Action Policies*. Report to DG Climate Action by Ecofys and Carbon Counts.

The political focus today, and the scope of this study, is on the latter – covering techniques involving emerging CO_2 transformation technologies in the fields of:

1. Chemicals
2. Synthetic fuels
3. Mineralisation.

These technologies can produce a wide range of industrial and consumer products, including:

- Intermediate chemicals (e.g. formic acid), and final products integrating CCU-derived materials, such as polyurethane or polycarbonate (e.g. foam sheets for furniture production; sunglasses; crash helmets etc.);
- Drop-in substitute fuels (e.g. methane), fuel additives for blending (e.g. methanol), or as a pathway to higher chain hydrocarbons through e.g. methanol to olefins (MTO) pathways or via Fischer-Tropsch (F-T) synthesis;
- Building aggregates, constructions blocks and pre-cast concrete.

In general, direct or non-conversion techniques tend to be commercially viable today, at least under certain niche circumstances, and the primary route – using CO_2 for enhanced oil recovery – is associated with geological storage of CO_2 for climate change mitigation purposes. As such, promotion of its use tends to be covered under the ambit of CCS policy initiatives. These technologies are not considered in this study.

On the other hand, CCS policy tends not to cover *conversion* technologies because of the fundamentally different nature of the processes under consideration, and, more importantly, uncertainties regarding the net GHG emission reduction benefits and the long-term isolation from the atmosphere of the CO_2 sequestered in CCU-derived products (as discussed further in Section 4). Consequently, the prospect of linking CCU technologies with climate policy – and promoting it through mechanisms designed to incentivise emission reductions such as carbon pricing (tax or trading) – presents some potential challenges.

A brief review of each CCU conversion technology group is provided below.

2.1 CO_2 to chemicals

There are various pathways through which CO_2 can be utilised to produce chemicals. These include the following:

1. Production of important base chemicals, such as: methanol, urea, carbon monoxide (CO), methane (CH_4; via methanation), formic acid etc.;
2. Algae systems (from which chemicals may be extracted for use);
3. Bicarbonate production;
4. Plastics (polycarbonate and polymers).

On the whole, pathways 1 and 2 generally lead to fuel production or other uses (e.g. nutraceuticals from algae; see below), although the range of base chemicals that can potentially be produced from CO_2 form building blocks for a wide number of other chemical production processes. Urea production using high-purity CO_2 off-gas streams from the Haber-Bosch ammonia production process has been widely used for more than 50 years and therefore is not considered as a novel application of CCU for widespread deployment today. Pathway 3 is achieved through a mineralisation process (see below). Consequently, the primary chemicals pathway for considering CCU today is widely regarded to be for plastics production.

Polymers are traditionally produced from methanol and ethylene derived from petrochemicals, and involve the use of phosgene, which is highly toxic. The pathway involving CO_2 sees the use of the same feedstocks as conventional production, such as epoxide derived from ethylene and methanol, but then using CO_2 in a carboxylation reaction with a zinc-based catalyst to produce polycarbonates such as polypropylene carbonate and polyethylene carbonate. The resulting materials can contain as much as 50% CO_2 on a weight-for-weight basis.

In recent years, several firms have made advances in CO_2-based polycarbonate production, including Novomer (USA) and Bayer/Covestro (Germany) – see Section 3 below.

2.2 CO_2 to fuels

The CO_2 to fuels pathways involves a broad category of CCU technologies covering a wide variety of pathways that can lead to the production of viable fuels. These include:

1. Water splitting with electrolysis (H_2O + *electricity* → H_2 + O) and conversion of H_2 with CO_2 (or CO derived from CO_2) in various processes including:
   - Hydrogenation (direct conversion of $H_2 + CO_2 \rightarrow CH_3OH$ (methanol or 'renewable methanol'))
   - Methanation/Sabatier reaction ($CO_2 + 4H_2 \rightarrow CH_4$ (methane) + H_2O)
   - F-T synthesis (an integrated hydrogenation and hydrogenolysis process or in part of a reverse water-gas shift process)

   These techniques can produce a number of fuel substitutes, including methane, methanol and dimethyl ether (DME) which can respectively be used as synthetic natural gas (SNG), direct blend products for petroleum or diesel, or in all cases as base chemicals for further conversion to alkanes and aromatics through e.g. MTO or other processes.
2. Algae production, with CO_2 acting as a growth accelerator, with either direct oils such as ethanol produced by the microbes and/or extraction of oils from the biomass. Alternatively, the biomass may be anaerobically digested to produce usable fuels (e.g. methane)
3. Formic acid production through direct CO_2 reduction, or electro-reduction, and subsequent use as a H_2 carrier in e.g. solid oxide fuel cells.

In all cases the thermal efficiency of the process is low, meaning the primary source of energy is key. In order for CCU to offer a sustainable pathway to fuels production, the source of energy would need to come from low carbon or renewable sources such as:

- Biomass (through pyrolysis gasification pathways to produce H_2 and CO – e.g. the 'integrated biorefinery' concept);
- Solar (e.g. through photocatalytic water-splitting as part of an artificial photosynthesis process);
- Other renewables, such as wind, hydropower, solar photo-voltaics (PV), or geothermal energy (as applied by CRI in Iceland) – ideally at off-peak times – as a source of electricity for electrolysis/electrocatalytic water-splitting;
- Nuclear energy (for electrolysis of water).

The type of catalysts used is also an issue for economic viability and environmental sustainability.

2.3 CO_2 for mineralisation

As for other CCU technologies, there are a variety of pathways by which CO_2 can be used in commercial mineralisation processes. The basic process involves the chemical conversion of CO_2 into solid inorganic carbonates and is reliant on the presence of alkaline or alkaline-earth oxides. The process occurs naturally in both natural (weathering of silicate rocks) and man-made (e.g. concrete) environments, and generally provides for fairly long-term sequestration of CO_2.

The main pathways for CO_2 mineralisation are:

1. *Carbonate mineralisation*, in which CO_2 is reacted with calcium or magnesium silicates – such as olivine (MgSiO4) and wollastonite ($CaSiO_3$) – to form calcium or magnesium carbonates, thereby providing CO_2 storage on a geological time scale. In addition to the

fact that CO_2 is permanently stored, carbonate mineralisation also has a potentially very large capacity: the calcium and magnesium carbonate mineral rock deposits on earth are theoretically sufficient to fix all the CO_2 that could be produced by the combustion of all available fossil fuel reserves (Lackner *et al.*, 1995). The natural carbonation reaction is, however, very slow. Therefore, a key challenge for large-scale industrial deployment lies in the acceleration of the carbonation process, using heat, pressure, and mechanical and chemical pre-treatment of the mineral (Centre for Low Carbon Futures, 2011).

2. *Sodium bicarbonate* ($NaHCO_3$) *production,* using the CO_2 in contact with either sodium hydroxide (NaOH) or with soda (Na_2CO_3) as applied by e.g. Skyonic in its 'Skymine' process.
3. *CO_2 concrete curing*, in which CO_2 (either in on-site flue gas or as a captured CO_2 stream) is combined with limestone and stored in precast concrete products. Concrete curing with CO_2 limits the need for heat and steam during the curing process.[1] This technology is still in development and its competitiveness with traditional methods of curing concrete will depend on whether or not it will reduce costs (National Energy Technology Laboratory, 2013). A significant technical challenge is to ensure that any changes in the curing process do not compromise the performance of the concrete (Global CCS Institute, 2011).
4. *Bauxite residue carbonation*, in which CO_2 can be injected into bauxite residue slurry to partially neutralise it, during which the CO_2 is converted to mineral form. The resulting product has a slight alkalinity and can be used as an aggregate for mine reclamation or construction, or to amend acidic soils (*ibid*).

Several firms have developed mineral carbonation technology over recent years, including Skyonic Corporation and Calera (USA) and Carbon8 (UK) – see Section 3 below. Bauxite residue treatment has been deployed on a limited commercial basis where factors allow - for example, to stabilise alkaline mine tailings from bauxite processing (known as "red mud") at Alcoa's Kwinana refinery in Western Australia.

2.4 Technology status

The broad scope of technologies and sectors covered under the ambit of CCU technologies means that there is a wide variation in the status of technologies and applications. Current activities span laboratory-scale experiments through to larger demonstration projects and commercial operations, producing a wide range of products.

A range of recent research has highlighted this variability and has attempted to make generalised assessments of technology readiness (e.g. Centre for Low Carbon Futures, 2011; Global CCS Institute, 2011; European Commission, 2013; National Energy Technology Laboratory, 2013; Department of Energy and Climate Change and Department of Business, Innovation and Skills, 2014). The body of literature on the topic of CCU does not, however, offer any clear, definitive view on the actual technological readiness level (TRL) of certain CCU applications, or

[1] The curing process of manufacturing concrete is essential to the concrete having sufficient strength and durability, as well as other properties that are important in the finished product (NETL, 2013).

which CCU technologies are the most promising for widespread future uptake. An up-to-date estimate of the status of different CCU technologies is set out below (Table 2.1).

Table 2.1 CCU technology readiness

CCU category	CCU technology	Research	Demonstration	Economically feasible under certain conditions	Mature market	TRL
CO_2 to fuels	Hydrogen (renewable methanol etc.)					**TRL 5-7**
	Hydrogen (formic acid)					**TRL 5**
	Algae (to biofuels)					**TRL 3-5**
	Photocatalytic processes					**TRL 3**
	Nanomaterial catalysts					**TRL 2-3**
CO_2 Mineralisation	Carbonate mineralisation					**TRL 3-7**
	CO_2 concrete curing					**TRL 5**
	Bauxite residue carbonation					**TRL 8**
Chemicals production	Sodium carbonate					**TRL 6-8**
	Polymers					**TRL 3-6**
	Other chemicals (e.g. acetic acid)					**TRL 9**
	Algae (for chemicals)					**TRL 3-5**

Source: Based on: European Commission, 2013, Department of Energy and Climate Change and Department of Business, Innovation and Skills, 2014, and expert judgement from the consulting team. TRL classification based on European Commission, 2014.

The next section (Section 3) provides a brief overview of the status CCU technology development in different parts of the world.

3 CCU ACTIVITY AROUND THE WORLD

This section aims to provide an overview of CCU-related activities currently ongoing at the time of writing. As noted below, generating a full picture of activities is challenging due to the diffuse and evolving nature of the sector. Therefore, results presented here should be considered as indicative rather than definitive of the current status of activities globally.

3.1 Current status of CCU operations

Presently there is no centralised global resource available to identify CCU projects around the world. Efforts have been made, however, to bring such information together, most notably the SCOT ("Smart CO2 Transformation") database (http://database.scotproject.org). TU Berlin has also produced a searchable map (www.entrepreneurship.tu-berlin.de/ccu/), while other researchers have similarly sought to track CCU activity and present it in a map format (Zakkour, 2013).

The SCOT database is probably the most advanced source of information on the status of CCU around the world available today. Now officially completed, the SCOT Project was supported by the EU's seventh Framework Programme (FP7; see Section 3.5 below). The main objective of the project was to define a strategic European research and innovation agenda in the field of CCU. Its database appears to be focused towards European activity and may not fully reflect activity elsewhere, perhaps a result of its funding source. Summary data from the database is presented below (Table 3.1).

Table 3.1 Summary of CCU activities by world region

Region	Funding Activity	Project
United States	Not listed	49
Canada	Not listed	10
Europe	34	146
Japan	Not listed	2
Korea	Not listed	2
China	Not listed	2
India	Not listed	-
Australia	Not listed	4
Others	Not listed	1
Global (total)	Not listed	**212**

Source: SCOT database, http://database.scotproject.org/.

These sources of information in the SCOT database are understandably limited in their detail and degree of reliability, given the fluid nature of the CCU sector as a whole. Caution should therefore be exercise in making use of the information supplied, particularly as it tends to be unclear on the source information. For example, the database exhibits some confusion between project types and also lacks clarity in respect of the scale of activity. Certain entries are merely funded activities, some are R&D projects, while others are operational sites. In general it is difficult to track the precise progress of these activities, as many start-ups receive limited funding, achieve press coverage and operate for a number of years, but then disappear. This is evident with certain recipients of American Recovery and Reinvestment Act (ARRA) funding, as distributed from 2009 onwards (see below).

For this project, we have attempted to take account of these factors and improve the granularity of information. Our estimates show that around 127 CCU projects are, or have recently, been in operation worldwide at the current time. These range in scale from small-scale demonstration projects to commercial operations. It should be noted that our database is also non-exhaustive and has fewer entries than the SCOT database (although we have sought to filter the estimates to only active projects). On this basis, the results of our analysis should also be treated with caution subject to provision of additional resources and effort to verify all activities.

Compiling the estimates outlined has provided insight into the challenges of gaining a full and clear picture of all activities that are ongoing – or that have concluded – within the field of CCU to date. This observation notwithstanding, what is clear from the existing data sources and the data collated for this project is that global CCU activity:

- Is taking place in many parts of the world, primarily but not solely in North America and Europe;
- Involves a wide range of technologies covering many industrial sectors, including chemical, steel, cement, automotive and energy; and
- Encapsulates projects at widely differing levels of conceptual maturity (TRL), from the many at the proof of concept and bench stage, to the far smaller number that are approaching, or that have reached, commercial viability.

The following sections attempt to provide a regional snapshot of the current status of CCU development covering both government views and types of support being provided.

3.2 Global

Much CCU activity is global in nature, often involving international project collaboration between academia and multinational corporations, and funding sources that are open to all. Policy and government funding for CCU is generally national and regional in focus, however. This section highlights the most noteworthy global activities.

As described above, the **Global CO_2 Initiative** is a programme that advocates a mix of policy, research funding, collaboration and infrastructure improvements to accelerate commercial deployment of CCU. Launched in January 2016, the initiative and its innovation arm, CO_2 Sciences Inc., were created to realise the ambitious goal of capturing 10% of global CO_2 emissions and transforming them into valuable products. CO_2 Sciences plans to grant up to US$400 million over the next ten years to qualified research applicants throughout the world (Global CO_2 Initiative, 2017).

In 2011, the **Global CCS Institute** published a wide-ranging report into the industrial use of CO_2 in the context of accelerating uptake of CCS more widely (Global CCS Institute, 2011). The report has two parts, the first of which investigates and evaluates the full range of CO_2 reuse technologies, ranking them according to specified criteria, with the second undertaking an economic and commercial evaluation of CO_2 reuse. The Global CCS Institute report concluded that most of the emerging reuse technologies still had years of development ahead before they reach the technical maturity required for deployment at commercial scale. It identified mineralisation technologies (mineral carbonation and concrete curing) as best placed to accelerate the use of concentrated streams of CO_2 and permanent sequestration of CO_2. However, this requires a readily available alkaline brine resource to avoid high energy consumption and a potential increase in net CO_2 emissions. Based on current and forecast markets, the report concludes that potential CO_2 reuse demand is too small for it to make a material contribution to global CO_2 abatement, and it does not provide a material alternative to conventional geological storage at the scale required. The Global CCS Institute followed its report with a 2016 webinar on the role of CCU in climate change mitigation (Global CCS Institute, 2016) where similar comments were made by expert participants.

Notwithstanding the generally weak forecasts for CCU and emission reductions, interest is continuing to grow. For example, February 2017 marks the eighth of the '**Global CO_2 Utilization Summits'**, a conference focussed on the reuse of CO_2 emissions and their conversion into profitable, sustainable materials. Held in venues across the world since 2013, these conferences seek to provide a comprehensive progress update on the global CO_2 utilisation industry, including the outlook for growth and updates on the latest technological advancements.

It is also worth noting that the **Mission Innovation** clean energy initiative may have implications for CCU. It is a landmark commitment launched in 2015 by 20 countries and the EU to dramatically accelerate public and private global clean energy innovation to address global climate change, provide affordable energy to consumers, and create additional commercial opportunities in clean energy (Mission Innovation, 2017).

Regional updates are outlined below which highlight the status of CCU within mainstream climate policy, studies undertaken, and both public and private funding activities.

3.3 United States

Is CCU part of any mainstream climate policies?

CCS and CCU are overseen by the DOE and have, to date, been actively supported by a range of policy initiatives, grants and incentives. In August 2016, the DOE published a white paper on carbon capture, utilisation and storage (CCUS) (Department of Energy, 2016), identifying it as a key pathway to addressing the need for clean energy: '*CCUS technology is necessary to meet climate change mitigation goals at the lowest possible cost to society… A combination of tax incentives and research, development, demonstration, and deployment (RDD&D) will be critical to developing transformational carbon capture technologies and to driving down the costs of capture*.' It is important to note, however, that in the US, the term CCU applies to CO_2-enhanced oil recovery, which is a core part of its strategy for promoting CCS. In terms of 'beneficial use of CO_2', the NETL (2014) recently concluded that '*CO_2 utilization will not be effective as a tool to mitigate GHG emissions by itself—largely because the CO_2 demand induced by implementing these opportunities is projected to be only a small fraction of expected supply*'

The **Clean Power Plan** is a federal policy designed to strengthen the shift to clean energy by setting standards for power plants and goals for states to cut their CO_2 emissions, setting a national limit on CO_2 pollution produced from power plants (Environmental Protection Agency, 2015; see Section 6.5.1). States are free to reduce emissions by various means, including the use of CCU (subject to meeting various requirements as outlined below).

An amendment to the 45Q tax credit for sequestration to include various beneficial uses of CO_2 has also been proposed in 2016 (see Section 6.5.1).

What studies has government done to help inform policy?
In 2013, NETL published a comprehensive comparison of CCU technologies, based on a number of economic, market/demand, logistical and technological criteria (National Energy Technology Laboratory, 2013). A field of 35 CCU technologies was narrowed to 12 that offered the best potential, with detailed viability calculated on a final five technologies, namely:

1. Clathrate desalination
2. Algae cultivation
3. Methanol production
4. Enhanced geothermal systems (EGS)
5. Concrete curing.

What government funding has been available?
The DOE has actively pursued CCUS demonstration projects in the industrial sector, with US$1.4 billion in deployment funding from the 2009 **American Reinvestment and Recovery Act** (ARRA) committed to date, of which US$100 million was allocated to industrial CO_2 recovery and beneficial uses of CO_2. Several CCUS demonstration projects have received federal government funding through public-private partnerships, with some also able to access additional incentives, such as the IRS Section 45Q tax credit and "private activity bonds" (bonds for specific projects with favourable tax treatment). The last President's proposed US Budget for fiscal year 2017 put forward a doubling of the federal investment in clean energy by 2021 and included expanded RDD&D for CCUS technology. It is also worth noting that the DOE has been provided with around US$10 million in research funding for beneficial use technologies despite not making any appropriations for such funds – the funding has been directly authorised by the Senate suggesting direct political interest in the technology (USE DOE, 2017, *personal communication*). Future arrangements will be determined by the new Presidency.

Grants are awarded via the DOE Office of Fossil Energy carbon storage programme, in particular its Carbon Use and Reuse research and development portfolio.

What private-sector and academic activity has there been?
The privately funded **NRG COSIA XPRIZE**[1] was launched in September 2015 to incentivise the development of technologies that convert CO_2 emissions into valuable products. With a total fund of US$20 million, XPRIZE takes the form of a global competition, with competing teams scored on how much CO_2 they convert and the net value of their products. It has two tracks – one focused on testing technologies at a coal power plant and another at a natural gas power plant. Round 1 completed in October 2017, when 27 teams were selected to move onto Round 2, in which they will demonstrate their technologies in a controlled environment (such as a

[1] NRG is a US power utility, COSIA is the Canadian Oil Sands Industry Association.

laboratory), using a simulated power plant flue gas stream. This concludes in December 2017. In each track, up to five teams will share a US$2.5 million prize and move onto Round 3. For Round 3, the teams will demonstrate technologies under real-world conditions, at a larger scale using actual power plant flue gas. Concluding in March 2020, one winner from each track will be awarded a US$7.5 million grand prize (NRG COSIA XPRIZE, 2017).

The US also has an active corporate sector in the field of CCU, with around 53 companies and research teams claiming to have pilot-, demonstration- or commercial-scale CCU projects. Notable companies in the sector include Alcoa, Calera Corporation, Novomer, Newlight Skyonic, LanzaTech etc. A summarised snapshot of activities drawn from our database (described previously) is presented below (Table 3.2).

Table 3.2 Summary of US-based CCU project activities

		TYPE				
		Chemical	Fuels	Mineralisation	Other	Total
SCALE	Bench/R&D	4	8	2		**14**
	Commercial	2	1	1		**4**
	Demo	2	4	2		**8**
	Pilot	10	8	6		**24**
	Unclear				3	**3**
	Total	**18**	**21**	**11**	**3**	**53**

3.4 Canada

Is CCU part of any mainstream climate policies?

While the Federal Government, alongside eight of the ten provinces and three territories, signed the Pan-Canadian Framework on Clean Growth and Climate Change on 9 December 2016, CCU is not mentioned, and there appears to be no formal federal position on CCU.

What studies has government done to help inform policy?

No studies by the Canadian government could be found.

What government funding has been available?

Emissions Reduction Alberta (ERA, formerly Alberta Climate Change and Emissions Management Corporation) is running **Grand Challenge: Innovative Carbon Uses**, seeking projects to make '*significant and verifiable GHG reductions by converting CO_2 emissions into new carbon-based products and markets*'. ERA has committed CA$35 million in funding in a multi-stage event, focusing on projects that can be commercialised in Alberta by 2020, and reduce GHG emissions by 1 Mt/year. The stages are detailed in Table 3.3.

Table 3.3 ERA Grand Challenge

Round	Funding Activity	Dates
1	Award of CA$12 million through 24 grants of CA$0.5 m	Awards completed in April 2014
2	Submissions invited from applicants with developed technology that can achieve net annual CO_2 reduction of >1 million tonnes; a maximum of five groups will be selected each to received CA$3 million in development grants	Currently active; successful projects to be announced in 2017
3	Five Round 2 winning groups will have two years to develop and demonstrate the required CO_2 reduction, when a final report is required; one of the five groups will be selected to receive a CA$10 million grant to fund technology commercialisation in Alberta	Final grant to be awarded in 2019

ERA is funded by Alberta's large emitters who have the option to pay into the Climate Change and Emissions Management Fund for purposes of compliance if they are unable to meet emissions reduction targets set under the Specified Gas Emitters Regulation of 2007.

What private-sector and academic activity has there been?

Canada also has an active corporate sector in the field of CCU, with around 16 companies and research teams claiming to have pilot-, demonstration- or commercial-scale CCU projects. Notable companies in the sector include: Carbicrete, Carbon Cure, Mantra Energy, Pond Technologies, Quantiam Technologies etc., as summarised below (Table 3.4).

Table 3.4 Summary of Canada-based CCU project activities

		TYPE				
		Chemical	Fuels	Mineralisation	Other	Total
SCALE	Bench/R&D	2	3	1		**6**
	Commercial					**0**
	Demo	2				**2**
	Pilot	2	1	3		**6**
	Unclear				2	**2**
	Total	**6**	**4**	**4**	**2**	**16**

3.5 Europe

Is CCU part of any mainstream climate policies?

The EU currently has no official policy position on CCU, and EU policy packages (e.g. from the Directorate-General for Climate Action [DG CLIMA]) do not define the term itself. However, in September 2015 the EU published an update of its Strategic Energy Technologies (SET) Plan, which aims to accelerate the development and deployment of low-carbon technologies. The update includes Action 9 on CCS and CCU: *'Step up research and innovation activities on the application of CCS and the commercial viability of CCU'* (European Commission, 2015a).

During 2016, EU stakeholders contributed to the SET Plan *Declaration of Intent on Strategic Targets in the Context of Action 9*, to define strategic research and innovation targets, resulting in an agreed specific target for 2020: '*Set up of one Important Project of Common European Interest (IPCEI) for demonstration of different aspects of industrial CCU, possibly in the form of Industrial Symbiosis*' (European Commission, 2016a). In its 2016 report on SET Plan progress, the Commission reiterated this target, stating that '*The key objectives for CCS/U … are to deliver the commercial scale demonstration of the full CCS/U value chain, and to reduce the costs of CO_2 capture through research and innovation'* (European Commission, 2016b).

What studies has the EU done to help inform policy?
The EU's work in support of climate policy centres on SETIS, the Strategic Energy Technology Information System, led and managed by the Joint Research Centre of the European Commission. SETIS has published a factsheet describing CCU and setting out its associated barriers and needs, relevant industry and EU action, its current and future potential, and stakeholder involvement (European Commission, 2016c).

What EU funding has been available?
The EU supported a number of CCU initiatives within its seventh Framework Programme for Research and Technological Development, known as FP7, which ran from 2007 to 2013, including the SCOT project referred to previously.

The EU's latest R&D support programme following on from FP7, named 'Horizon 2020', runs from 2014 to 2020. It has a stronger focus on delivering economic growth, and has launched several relevant calls to help the research community develop CCU technologies to the industrial demonstration stage (European Commission, 2016d; Table 3.5).

Table 3.5 EU calls for proposals under Horizon 2020

Name	Year	Detail
SPIRE 5	2016	Potential use of CO_2/CO and non-conventional fossil natural resources in Europe as feedstock for the process industry
LCE 25	2016	Utilisation of captured CO2 as feedstock for the process industry
SPIRE 8	2017	CO2 utilisation to produce added value chemicals
SPIRE 10	2017	New electrochemical solutions for industrial processing, which contribute to a reduction of CO2 emissions
BIOTEC 05	2017	Microbial platforms for CO2-reuse processes in the low-carbon economy
NMBP 19	2017	Cost-effective materials for "power-to-chemical" technologies
NMBP 20	2017	High-performance materials for optimizing CO_2 capture

The promotion of CCU technology can be viewed more widely as tying into a number of the European Commission's priorities, including the challenge of attaining the circular economy (European Commission, 2014b). This dovetails with the Commission's objectives under Horizon 2020, with which it aims to demonstrate the opportunities for moving towards a circular economy at European level with large-scale innovation projects.

To complement its R&D support, the European Commission has also launched a €1.5 million **Horizon Prize for CO_2 Reuse** to further support and accelerate emissions-saving innovation in CCU. The prize will be awarded in late 2019 to the most innovative product reusing CO_2. The winning product should demonstrate a significant reduction in net CO_2 emissions while overcoming key technical, commercial and financial barriers. The criteria are: net CO_2 emission reduction; overcoming barriers; commercialisation and scalability; and environmental impacts. (European Commission, 2016e; European Commission, 2017).

The **IPCEI** has been highlighted by the European Commission as a potential vehicle for CCU projects of strategic importance for the EU economy. It represents a loosening of state aid rules, allowing for a greater variety of support measures (e.g. repayable advances, loans, guarantees or grants) and funding for up to 100% of the funding gap. It allows state aid to be granted for '*the initial industrial deployment (i.e. beyond R&D) of a new product with high research and innovation content and/or a fundamentally innovative production process*' (European Commission, 2014c). The Renewable Energy Directive was also revised in 2015 to allow CCU-derived fuel to qualify as renewable transport fuel (see Section 7.1.3 below), and activities are ongoing to amend the EU GHG Emissions Trading Scheme (ETS) to include CCU activities, including the provision of new *Innovation Fund* monies (or 'NER400+') scheduled for phase IV of the ETS (2021-2030) (see Section 6.2.1 below).

What private-sector and academic activity has there been?
Key CCU players in Europe are in the process of creating ASCOT, the *European Association for CO_2 Transformatio*n, which builds on the SCOT project. Further detail on ASCOT is expected in the near future.

Further private sector and academic activity is discussed by member state below. A summary of European activities is based on our database is presented below (Table 3.6).

Table 3.6 Summary of European-based CCU project activities

		TYPE				
		Chemical	Fuels	Mineralisation	Other	Total
SCALE	Bench/R&D	9	8	2	1	**20**
	Commercial	2	2	1		**5**
	Demo	3	5			**8**
	Pilot	4	6	4		**14**
	Trial			1		**1**
	Total	**18**	**21**	**8**	**1**	**48**

Includes: Germany, Italy, Spain, France, Austria, Belgium, UK, Finland, Netherlands, Portugal (EU Member States) and Iceland, Switzerland, Norway (EEA member countries).

3.5.1 Germany

Is CCU part of any mainstream climate policies?

CCU is mentioned in the latest **Climate Protection Plan 2050** as a key technology for reducing industrial CO_2 emissions, albeit with no definitive target – the focus is on R&D within industry to develop CCU-related technologies (Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety (BMUB), 2017).

What studies has government done to help inform policy?

The Wuppertal Institute for Climate, Environment and Energy has conducted a detailed study into CO_2 reuse in the North-Rhine Westphalia region of Germany – the industrial heartland of Germany – evaluating sources, demand and utilisation for CO_2 and providing recommendations for R&D, politics and economics to facilitate CO_2 utilisation options (Wuppertal Institute, 2015).

What government funding has been available?

Federal funding for CCU research is organised by the Federal Ministry of Education and Research (BMBF), and is summarised in Table 3.7.

Table 3.7 German federal funding for CCU research

Name	Year	Activity
Technologies for Sustainability and Climate Protection: Chemical Processes and Use of CO_2	2009	33 collaboration projects between academia and industry supported with approximately EUR 100 million, to which industry added a further EUR 50 million
Innovation Initiative Industrial Biotechnology	2011	Alliances to replace fossil resources with biotechnological products; supported by funding of EUR 100 million; three of five collaborations selected were dedicated to CCU technologies
r+Impuls	2014	Projects with a technology readiness level of at least 5 can receive support for the risky upscaling from pilot plant to the first industrial demonstration plant
CO2Plus – Broadening the Raw Material Base by CO_2 Utilisation	2015	To support the integration of CO2 into value-added chains, e.g. polymers and chemicals, integrating the chemical and the process industries; selected projects launched in the second half of 2016
Biotechnology 2020+	2015	Funding for basic technologies for next generation biotechnological processes; supported three selected projects working on microbial or enzymatic activation of CO_2
Kopernikus Projects for the Energy Transition	2015	EUR 10 million per annum will be awarded to power-to-X projects up to 2025; focus on storage of energy from flexible renewables by the generation of chemical energy carriers

What private-sector and academic activity has there been?

A range of research and commercially led projects have been funded, or continue to be funded at the time of writing. Our estimates suggest around a total of 15 demonstration to commercial-scale activities are currently ongoing, primarily focussed on fuels and chemicals production, and involving firms such as Covestro (formerly Bayer Material Science), BASF, Evonik and ETOGAS (recently acquired by Hitachi Zosen Innova).

3.5.2 United Kingdom

Is CCU part of any mainstream climate policies?

Although the UK government has funded various CCU-related activities, it has yet to incorporate the technology into mainstream UK climate policy. For example, it is not mentioned in the UK's carbon budgets, which are produced every four years and are legally binding.[1]

What studies has government done to help inform policy?

Government departments have produced at least two reports on CCU, for example the 2014 study published by the energy and business departments looks into the potential for CO_2 capture in the UK cement, chemicals, iron and steel and oil refining sectors (Department of Energy and Climate Change and Department of Business, Innovation and Skills, 2014). In 2016, the Department for Business, Energy & Industrial Strategy (BEIS) initiated a new study to assess the potential of CO_2 utilisation in the UK (Ecofys, 2016). The results of the latter have yet to be published.

What government funding has been available?

While the UK has no national programme specifically aimed at supporting CCU activity, the UK government uses a variety of mechanisms to promote CCU research and development. The Engineering and Physical Sciences Research Council (EPSRC) provides government funding in the form of grants for research and postgraduate study mainly to universities in the UK. Its recent grants to UK universities include funding of GB£6.4 million for research into CCU. The UK's innovation agency, Innovate UK, also provides funding for a limited number of CCU-related projects, such as the 'Green Ammonia' project implemented by the University of Sheffield with ITM Power and Waitrose (supermarket chain).

What private-sector and academic activity has there been?

The UK has at least three active commercial CO_2 mineralisation projects (2 x Carbon8 facilities plus Cambridge Carbon Capture), and at least a further six or seven projects at bench-, demonstration- and trial-scale including various spin-offs from UK universities. The focus is mainly on mineralisation, although at least two each of fuels and chemicals projects are active. At least one CO_2 to fuels developer – Air Fuels Limited – went bankrupt in recent years.

3.5.3 France

Is CCU part of any mainstream climate policies?

France's **National Low-Carbon Strategy** (SNBC), launched in November 2015, refers to the likelihood of R&D making possible the large-scale development of capture and storage or use of carbon, and the development and deployment of CCU technologies in the chemical industry to achieve carbon reduction targets (Ministry for the Environment, Energy and the Sea, 2015).

What studies has government done to help inform policy?

The French Environment and Energy Management Agency (ADEME) conducted a study in 2014 that resulted in identification of the most promising CCU pathways involving chemical

[1] The 5th (latest) Carbon Budget was adopted by Government in 2016, and sets emission reduction commitments to 2032. The topic of CCU is not mentioned in the supporting analysis.

conversion and the main actions to be implemented in France to foster their emergence. Three processes were selected:

- Methanol synthesis by direct hydrogenation of CO_2;
- Formic acid synthesis by electro-reduction of CO_2; and,
- Sodium carbonate synthesis by aqueous mineralisation (ADEME, 2014).

What government funding has been available?
Since 2010, France has run several programmes to support CCU technologies, from research to development and demonstration. At the research level, CCU is included in the decarbonised energy programme run by ANR (French National Research Agency) and CCU appears in several innovation programmes dealing with different themes run by ADEME. There are also several projects at demonstration scale on power-to-gas or chemical conversion of CO_2 supported by the French government through its Investment for the Future programme (El Khamlichi, 2016).

ADEME established **Club CO2** in 2002. With ADEME as chair, it brings together actors from across industry and research and acts a clearing house for information, dialogue and good practice among its members on CCU research and technological developments. It encourages cooperation at a national level between public and private sectors, and it has overseen several research projects. Club CO2 has 30 members in total, and in 2011 produced a roadmap on the capture, transport, geological storage and re-use of CO_2 (CCUS; ADEME, 2010).

What private-sector and academic activity has there been?
Activity by private-sector actors on CCU is a little way behind the UK and Germany. The focus of four of the five identified activities in our database was on fuel production, with the leading actors being Solvay and GDF-Suez. All activities are at either bench- or pilot-scale.

3.6 Japan

Is CCU part of any mainstream climate policies?
CCS and artificial photosynthesis feature in the **New Low Carbon Technology Plan** (Bureau of Science and Technology Policy, 2013) under the list of potential low-carbon technologies, and this policy document may be the main driver of CCU in the future together with the **Cool Earth-Innovative Energy Technology Programme** (Ministry of Economy, Trade and Industry, 2008). The latter is focused on the development of essential innovative technologies for future low-carbon industrial development, and was established as a means to pursue their development and deployment.

In many programmes, CCU is often mentioned together with CCS as a potential technology to help to reduce CO_2 emissions while offering the economic potential to promote new technologies.

What studies has government done to help inform policy?
The Japan Ministry of Economy, Trade and Industry (METI) and New Energy and Industrial Technology Development Organization (NEDO) supported the **Carbon Dioxide Utilization Roadmap 1.0**, published in November 2016 by the Innovation for Cool Earth Forum. The

roadmap presents a global CCU commercialisation roadmap through to 2030 (Global CO_2 Initiative/ICEF, 2016).

The Research Institute of Innovative Technology for the Earth (RITE), funded by METI, promotes projects for the technological development of CO2 fixation and its effective use. In 2005, RITE published a report on such technologies, in which CCU is described and various kinds of CCU technologies are listed with a review of their GHG emissions reductions potential, and their cost and maturity.

What government funding has been available?
The Japanese government is planning to earmark a total of ¥10 billion over a period of 5 years.

What private-sector and academic activity has there been?
The main active player in CCU in Japan is Mitsui Chemicals. It has built a plant capable of capturing 100 tCO_2/year from petrochemicals production and is using this to generate methanol through a photocatalysis (artificial photosynthesis) route.

3.7 Korea

Is CCU part of any mainstream climate policies?
CCU activities appear to fall within Korea's CCS programme, the recently reviewed **CCS Master Action Plan (2010-2020)**, which was originally established in 2010 as part of Korea's intended Nationally Determined Contribution (iNDC) target under the UNFCCC Paris Agreement. The revised Korea CCS master action plan covers CCS RD&D activities in the period 2016-2030.

What studies has government done to help inform policy?
No studies by the Korean government could be found.

What government funding has been available?
The Korea Carbon Capture and Sequestration R&D Center (KCRC) has an innovative R&D programme for developing advanced CCS technology in three major research areas: post combustion capture, storage, and CO_2 conversion (utilisation). Its R&D activity includes the investigation of chemical and biological CO_2 conversion techniques to produce high added-value products utilising CO_2.

What private-sector and academic activity has there been?
KOGAS has been manufacturing dimethyl ether (DME) using from CO_2 since 2000 on demonstration and pilot scale plants in Korea, and has sought to build a commercialised process producing 3,000 tonnes per day of DME.

3.8 China

Is CCU part of any mainstream climate policies?
China has a number of climate policy documents that refer to CCUS, rather than CCU specifically. The most notable is the 2015 Roadmap for Carbon Capture and Storage Demonstration and Deployment, led by the National Development and Reform Commission (NDRC) in association with the Asian Development Bank. Whilst the term CO_2 utilisation is used, it is principally in the context of facilitating CCS or for CO_2-enhanced oil recovery. It does, however, refer to

recommending '*a gradual dual track approach of large-scale demonstration in low-cost opportunities utilizing captured CO_2 (CCUS) and parallel intensive research efforts to overcome remaining cost and energy penalty hurdles*.' (ADB, 2015, p. vii). China's INDC also discusses strengthening R&D for CCUS.

What studies has government done to help inform policy?
No studies by the Chinese government could be found.

What government funding has been available?
It is unclear whether the Chinese government has made funds available in this field.

What private-sector and academic activity has there been?
No specific firms or activities could be identified.

3.9 India

Is CCU part of any mainstream climate policies?
CCU does not appear in India's National Action Plan on Climate Change. India's iNDC under the UNFCCC Paris Agreement does not mention CCU, CCS or CCUS.

What studies has government done to help inform policy?
The Indo-UK Centre for Environment Research and Innovation (IU-CERI) was launched in 2016 to further research into low-carbon technology, including CCU. The Indian partner is CSIR-CIMFR (Indian Council of Science and Industrial Research, Indian Government) and leading universities, while the UK partner is the University of Greenwich. The collaboration will develop joint research and expertise with direct links to the Indian Government, businesses and communities.

What government funding has been available?
According to a study for the Global CCS Institute (Global CCS Institute, 2011), most Indian R&D activities related to CCS occur under the Department of Science and Technology (DST) of the Indian Ministry of Science and Technology. The DST set up the National Program on Carbon Sequestration Research in 2007 for both pure/applied research and industrial applications. Of the four areas of research identified under this programme, one comprised CO_2 sequestration through micro algae bio-fixation techniques, and a number of such projects were funded across India (TERI, 2013).

What private-sector and academic activity has there been?
The main private sector activity identified in India was the recent start-up by Carbonclean of a 60,000 tCO_2/year capture facility for the production of baking soda in Tuticorin Alkali Chemicals, Tuticorin, Tamil Nadu (Harrabin, 2017).

3.10 Australia

Is CCU part of any mainstream climate policies?
Australia's principal climate policy is the Emissions Reduction Fund (ERF), under which government will purchase low-cost abatement through reverse auctions to contribute towards the national GHG reduction commitment. CCU is not currently included among the 33 emissions reduction methods approved by the Clean Energy Regulator.

What studies has government done to help inform policy?

No studies by the Australian government could be found.

What government funding has been available?

The Commonwealth Scientific and Industrial Research Organisation (CSIRO), the federal government agency for scientific research in Australia, funded the creation of the CO2MOF network. This multidisciplinary research team drawn from seven institutions across Australia conducts research into the capture and use of CO_2 on an industrial scale using metal-organic framework (MOF) devices for catalytic conversion.

What private sector and academic activity has there been?

The only major private sector actors identified in Australia are Calix Limited (mineralisation) and Integrated Carbon Sequestration Pty Ltd. (mineralisation). The extent of operations of each was difficult to discern from publicly-available information.

4 POTENTIAL FOR CCU TECHNOLOGIES TO REDUCE GHG EMISSIONS

As noted in Section 1, although CCU technologies are increasingly being discussed in the context of climate change mitigation technologies, the basis for these discussions is unclear since the evidence base on which to make judgments is limited: few CCU researchers and industrial technology developers provide clear information on the energy, carbon and materials balance across their process. As such, the true mitigation potential of the technology is uncertain, driven by various challenges presented by the technology. To resolve this uncertainty, greater effort is needed to elaborate effective and usable approaches upon which to account for GHG emission reductions from CCU. A second factor is scale. Most studies conclude that the potential is small because of limitations on the demand for CO_2 for industrial applications (e.g. Metz *et al.*, 2005); however, more recently, various reports have suggested the opportunity could be much greater.

This section considers the nature of the challenges to accounting for GHG emission reductions from CCU, and the potential scale of emission reductions from CCU in pursuit of climate change mitigation goals.

4.1 Accounting for emissions reductions

The main technical challenge facing CCU is the low reactive state of CO_2 under standard conditions. This means that its utilisation presents an energy trade-off and/or a reduction in its activation energy requirement for reactions through the use of catalysts (Centre for Low Carbon Futures, 2011). As a result, the conditions under which CCU technologies could deliver CO_2 emission reductions tend towards niche circumstances where there is sufficient surplus energy – generated from renewable sources – and/or where substitution of the conventional production method leads to energy or materials gains during fabrication/synthesis (European Commission, 2013). CCU operations running on grid electricity and/or heat and power generated from fossil fuel fired plants are unlikely to offer net reductions in CO_2 emissions due to the energy balances of the process.

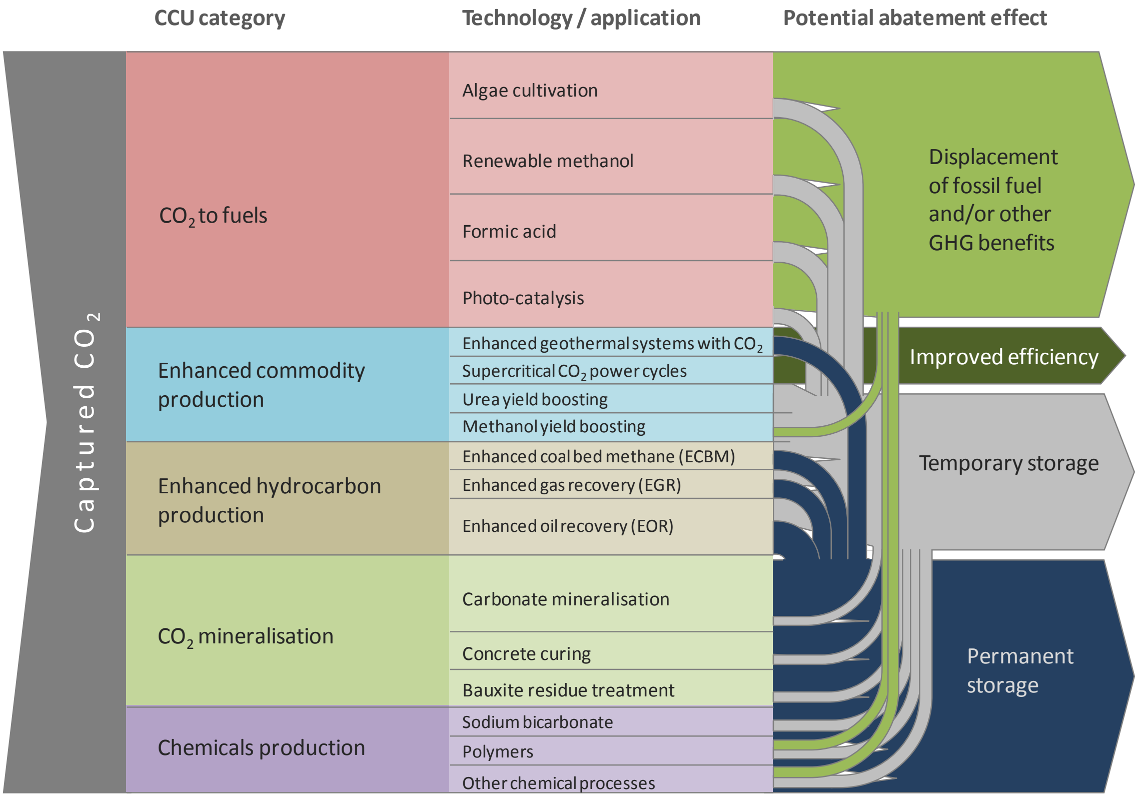
Another challenge is the source and quality of CO_2 that can be used in CCU applications. Most applications to date have involved the use of a fairly pure stream of CO_2, meaning that capture and purification of combustion exhaust gas will generally be required before use. As such, further energy and materials consumption is involved upstream of the CCU process. Research has been fairly limited in respect of the possibility of directly using flue gases in CCU applications; such developments could, however, offer a significant breakthrough for reducing energy and materials consumption, creating a clear advantage for CCU ahead of CCS. It is also worth noting that several commercial CCU ventures use bought-in CO_2 from unknown sources, typically CO_2 manufactured from natural gas (e.g. Carbon8).

Furthermore, many of the GHG emission reduction benefits of CCU involve substitution and displacement of other fossil-based alternative products on both the supply and demand side of the product value chain. On the supply side, the use of CO_2 as a feedstock may reduce the use of fossil-derived feedstocks such as crude oil or petrochemical derivatives, which could have net GHG emission benefits. Similarly, on the demand side, the production of CO_2-derived chemicals and fuels can displace fossil-derived alternatives such as petroleum. This creates spatial/geographical issues for emissions accounting which are difficult to identify (essentially a *boundaries* problem) and quantify (a *leakage* issue).

Finally, products derived from CCU technologies have variable lifespans, and can result in re-release of the CO_2 sequestered in the product back to the atmosphere upon use (e.g. fuels) or disposal (e.g. plastics). This presents temporal challenges for emission accounting in terms of the *permanence* of the emission reductions delivered by CCU.

These factors are summarised graphically in the partial Sankey diagram below (Figure 4.1), as prepared by the authors for the European Commission in 2013 (European Commission, 2013). The graphic attempts to characterise how different CCU pathways create different types of abatement effects: the green abatement outcome shows the substitution effect primarily from the CO_2 to fuels pathways, and also the temporary nature of the storage offered by this group in grey. The CO_2 to chemicals pathway is characterised by more complex abatement effects, with temporary, permanent and substitution effects. The diagram also shows the limited number of pathways leading to permanent storage, largely derived from CO_2 to mineralisation pathways.

Figure 4.1 Illustrative emission reduction pathways for CCU technologies



Source: European Commission, 2013

This is not a new finding. The IPCC SRCCS (Metz *et al.*, 2005) came to a similar conclusion when it wrote, in the context of industrial CO_2 uses, that:

> *'…this option is meaningful only if the quantity and duration of CO_2 stored are significant, and if there is a real net reduction of CO_2 emissions. The typical lifetime of most of the CO_2 currently used by industrial processes has storage times of only days to months. The stored carbon is then degraded to CO_2 and again emitted to*

the atmosphere. Such short time scales do not contribute meaningfully to climate change mitigation.

It also goes on to add that:

> *'Another important question is whether industrial uses of CO_2 can result in an overall net reduction of CO_2 emissions by substitution for other industrial processes or products. This can be evaluated correctly only by considering proper system boundaries for the energy and material balances of the CO_2 utilization processes, and by carrying out a detailed life-cycle analysis of the proposed use of CO_2. The literature in this area is limited but it shows that precise figures are difficult to estimate and that in many cases industrial uses could lead to an increase in overall emissions rather than a net reduction.'*

Thus, the issues of *boundaries*, *leakage* and *permanence* outlined above present a major challenge for recognising, accounting for, and rewarding CCU as a climate change mitigation technology:

- *Recognition* is difficult because the apparent abatement effect occurs across multiple parts of the CCU product value chain, making them difficult to discern since they rely on assumptions about the inputs to fabrication and product market dynamics (i.e. assuming perfect substitution and displacement of incumbents).
- *Accounting* is challenging because of both spatial and temporal factors, which do not fit easily to the typical source-based, annual reporting cycle adopted in GHG accounting approaches and the measurement, reporting and verification (MRV) of emissions *ex post*.
- As a result of these factors, allocating a carbon price *reward* to CCU technologies will be complex because of the multiple parties across the CCU product value chain that could be involved in delivering the full-life emission reductions that may be achievable.

Consequently, the design of policy approaches to incentivise the uptake of CCU needs careful consideration, as discussed in Part 2 below.

4.2 Scale of mitigation potential

The uncertainty regarding the type and pathways for GHG emission reductions created by CCU technologies mean that gaining an understanding of the overall potential for them to reduce emissions on a global scale is also challenging. Scaling up abatement estimates for a given CCU technology – where already a number of assumptions may have been made in the first place – is challenging and open to significant error. Such efforts inherently involve adding more assumptions about e.g. energy sources, materials sources, the capacity of industry and consumers to adapt to new technology, the capacity to overcome inherent industry inertia, and so on.

Over the past 12 years, various efforts have been made to evaluate this potential, and the results are extremely wide. A significant characteristic has been the tendency for estimates to increase over time, as described further below.

In 2005, the IPCC estimated that, for industrial CO_2 uses, '*the total amount of long-term (century-scale) storage is presently in the order of 1 MtCO$_2$/year or less, with no prospects for major increases*' (SRCCS, *op. cit.*). Some six years later, the Global CCS Institute (2011) provided a range of "order of magnitude" estimates of between 0.5-1.87 GtCO$_2$/year for future CO_2 demand for novel uses.[1] The numbers provided were for estimated CO_2 *demand*, rather than CO_2 *abatement potential*. Alternatively, at around the same time Det Norske Veritas (2011) suggested that the '*various utilization technologies together [including non-conversion techniques] have the potential to reduce CO_2 emissions by at least 3.7 Gt/year (approximately 10 % of total current annual CO_2 emissions), both directly and by reducing use of fossil fuels*'.

More recently, protagonists of CCU technologies have made greater claims about its potential. For example, Armstrong and Styring (2015) recently published what they describe as a 'realistic yet challenging' scenario for up to 1.34 GtCO$_2$/year being utilised by 2030. This equates to almost 4% of all global CO_2 emissions today. Again, this estimate is only for CO_2 demand, rather than CO_2 abatement. Even more recently, the Global CO_2 Initiative – in its work on a CCU Roadmap with CO_2 Sciences and the *Innovation for Cool Earth Forum* (ICEF; Global CO_2 Initiative/ICEF, 2016) – estimated that the main product groups involved in CCU could utilise around 7 GtCO$_2$/year by 2030, which equates to around 15% total global emissions today. This figure has been broadly adopted by the Global CO_2 Initiative as the basis for its overall aim, as outlined previously, namely to realise *'the ambitious goal of capturing 10% of global CO_2 emissions and transforming them into valuable products'* (Global CO_2 Initiative, 2016).

The various estimates from the literature are summarised below (Table 4.1).

Table 4.1 Estimates of CCU mitigation potential

Source	Year	Estimate (Gt/year)	Time period
IPCC	2005	< 1.0	Medium-term
GCCSI	2011	0.5 – 1.87 *	Future
DNV	2011	3.7	None provided
Armstrong and Styring	2015	1.34 *	2030
Global CO_2 Initiative/ICEF	2016	7 *	2030

* denotes CO_2 demand estimate rather than CO_2 abatement estimate

Mindful of the uncertainties described, Part 2 of this report reviews how CCU technologies are currently treated within a range of CCU accounting frameworks worldwide.

[1] Based on Table 1.4 in GCCSI (2011), excluding non-conversion uses.

PART 2: GHG ACCOUNTING RULES AND CCU

5 INTRODUCTION

Emissions accounting is a term that refers to rules and methodologies employed to compile a greenhouse gas (GHG) emissions inventory for a fixed period of time, typically one calendar year. Alternatively, rather than calculating the emissions inventory on a temporal basis, it could also apply on a unitised basis, such as tCO_2/t product (although this would also require a temporal dimension to be included at some stage). It is useful to consider two frames of reference when considering GHG emissions accounting approaches:

1. *Ex ante* assessment of GHG emissions for a particular product, project or programme using techniques based on life-cycle analysis (LCA). This approach involves making an estimate of the full range of GHG emissions associated with a product or activity covering extraction, manufacture, transport, construction and end of life, etc. It is often applied on a theoretical basis.
2. *Ex post* assessment, to compile a GHG inventory involving real-time measurement of emissions and the estimation of emissions over a given period of time. This approach can also be referred to as measurement, reporting and verification (MRV). It is used to measure emissions from an operational activity.

In terms of the former, life-cycle based *ex ante* assessments of GHG emissions of a given product, project, process or programme can help inform policy choices regarding the relative benefits of different technologies, although MRV is usually necessary to ensure effectiveness of technologies *ex post*. For example, such approaches can form part of a regulatory approval for a proposed infrastructure project (e.g. a new industrial development), or it can also be applied in product-based accounting, where it is used in some regulatory schemes on both an *ex ante* and an *ex post* basis, such as in low carbon fuel standards. The latter approach involving MRV is often applied to measure compliance and effectiveness of a GHG abatement policy, for example, an emissions trading scheme (ETS).

Various other considerations are also relevant to discussions on emissions accounting and MRV. Generally, *production-based accounting* approaches are used in climate change policy, where the anthropogenic emissions of GHGs are estimated for a country, for example, based on the amount of GHG emissions produced within its national borders, irrespective of exports and imports. Alternatives include *consumption-based accounting*, where a GHG inventory is compiled based on the emissions embedded in products consumed within, for example, a national economy, including imports and exports, or hybridised approaches involving *life-cycle emission accounting*, as described above. In addition, GHG accounting can also involve estimating the removal of GHGs from the atmosphere by sinks. This is typically accomplished on the basis of measuring annual stock changes in the carbon stored in various pools on managed lands (i.e. altered by human activities), such as agricultural land, forestry and wetlands.

The focus for the consideration of CCU technologies is on the use of MRV in production-based emissions accounting as generally applied in GHG policy frameworks, and life-cycle emissions accounting as sometimes applied to product policy.

5.1 Purposes and scale of emissions accounting

GHG emissions accounting, and the resultant GHG emissions inventories compiled using MRV methods, can be developed for a wide range of purposes and at different scales, including:

- global scale (total world GHG emissions, covering sources of anthropogenic GHG emissions to atmosphere and removals by GHG sinks)
- a country (a national GHG inventory of sources and removals by sinks)
- a sector (e.g. power, iron and steel, cement, transport, managed forestry, agriculture)
- an installation or facility (e.g. a factory or power plant)
- a corporation or organisation (a corporate GHG inventory. These may cover multiple installations, sectors and countries)
- a policy (e.g. domestic energy efficiency labelling; targets for low-carbon power generation)
- a programme (e.g. roll-out of solar water heater or efficient cooking stoves)
- a project (e.g. related to a specific infrastructural development or GHG mitigation activity)
- a product (e.g. product life-cycle GHG emissions accounting for a food item, for example, or as applied in low carbon fuel standards, for example)
- an event or activity (e.g. a 'carbon footprint' of a flight, rail or car journey, or all emissions associated with a conference, for example)
- an individual (a personal 'carbon footprint')

In each case, different approaches, tools and methods are typically used to take account of different features of the inventory being compiled, and a large and growing body of guidance exists providing methods for their development.

5.2 Accounting approaches for CCU

Taking into account the discussion in the previous sections, one of the key challenges today is understanding what purpose any emission accounting framework for CCU technologies should serve. In essence, this discussion is really about consideration of the policy choices available for promoting and incentivising uptake of CCU technologies. This could take several forms:

- *Industrial CO_2 emissions mitigation*: on the one hand, CCU creates a **GHG emission reduction at source** where the CO_2 is being captured from an anthropogenic fossil emission source, and used onsite or transferred offsite for use elsewhere. This characteristic lends itself to carbon pricing policy incentives, where a cost is attached to the emission of CO_2 (or a price paid for its reduction) at the installation/facility level. Effective installation/facility level GHG accounting/MRV is needed so that the CO_2 that is captured and utilised – and would have otherwise been emitted to atmosphere – is appropriately deducted from the capturing entity's GHG emission inventory, and the financial liability for the emission is removed.

- *Product-based life-cycle GHG improvement*: on the other hand, CCU-derived products – as discussed extensively in Part 1 – can have lower **product life-cycle GHG emissions** than alternatives in the market in relation to GHG emissions both up- and downstream of the point of production. This characteristic lends itself to policies that incentivise the supply and use of lower emitting products in the market, taking into account their whole-life emissions. In order to understand the scale of the emission reduction benefit compared to incumbent products, effective life-cycle GHG accounting is needed that quantifies the GHG benefits relative to other market alternatives which it is seeking to replace.

Neither approach is mutually exclusive, however. As such, there is probably not a single solution appropriate to the broad range of technologies captured under the ambit of "CCU".

Rewarding the **CO_2 emission reduction at source** can be effective in promoting the uptake of industrial CO_2 capture, since the benefit is accrued directly by the entity undertaking the capture. Issues arise, however, in allocating those benefits to the entity using the CO_2, unless they are the same entity. This would require transactions between the two entities to take account of the CO_2 value in order to share the benefit. This approach also poses some problems for environmental integrity and *leakage*. Firstly, although it would recognise that CO_2 is not emitted at the point of capture, it would not take account of the any GHG emissions occurring at the point of utilisation, unless again it is part of the same installation. Such approaches also cannot account for any GHG benefits or negative effects occurring up- and downstream in the product value chain. This could mean that although a payment is made for an emission reduction at source, the net emissions of the whole system may not be particularly beneficial, or perhaps may be even worse than comparable processes not utilising CO_2. Secondly, problems arise if the reduction is not *permanent*, for example, if the CO_2-containing product is sold into the market and the CO_2 simply emitted elsewhere over the short term outside of the facility's GHG inventory boundary. This means that the emission reductions claimed may not actually happen for very long – an outcome that will place the technology at odds with other competing technologies in the system which can deliver permanent emission reductions (e.g. CCS). It will also affect the environmental integrity of any tradable emission reduction units generated and sold by the facility/installation, since a claimed and credited "tonne reduction" didn't actually equal a "tonne reduction" across the whole life cycle.

A **product-based GHG reduction incentive** scheme can overcome some of these problems, but also presents some challenges of its own. Firstly, such approaches are difficult to implement because of the inherent uncertainty involved in looking at the full value chain GHG emissions for a product. These issues are not insurmountable, however, and are now widely used for products such as fuels (e.g. under low-carbon fuel standards; see below), but may be more challenging for CO_2 to chemicals pathways that could involve more complex and longer value chains with multiple intermediate steps. Additionally, such approaches mean the benefit is accrued only by the product producer, creating challenges to incentivise the uptake of CO_2 capture at industrial emission sources – unless effective benefit sharing arrangements are structured between the CO_2 supplier and user.

Alternatively, **both types of accounting (source *and* product) could be applied**. This would potentially involve applying a *double incentive* – by rewarding both the CO_2 emission reduction at source and also the full life-cycle GHG emissions. This might not be a problem for policy-makers if the objective is to rapidly promote the technology. But such an approach needs to ensure that it avoids *double counting* of the emission reductions achieved. Double counting should not be a problem, however, since the overall net GHG effects should be effectively accounted for at a national level (see Box 5.1).

Box 5.1 National GHG Inventories and CCU

Under the United Nations Framework Convention on Climate Change (UNFCCC), signatory Parties are obliged to compile national GHG inventories that provide a record of all emissions of anthropogenic GHGs from various source sectors, removals by carbon sinks, and changes in carbon stocks arising as a result of land use changes in its territory. It is applied for a given calendar year. The 2006 IPCC Guidelines for National Greenhouse Gas Inventories (2006 GLs; IPCC, 2006) are the most recent guidelines available to Parties, although not all Parties are obliged to use the most recent version.

For countries now making emission reduction pledges in the form of Nationally Determined Contributions (NDCs), the national GHG inventory will be critical for the "MRV" of progress being made in pursuit of agreed contributions.

For CCU, two key questions need to be considered to ensure effective national GHG accounting:

1. Whether CO_2 captured from an emission source and utilised in a product can be deducted from the capturing facility's GHG inventory and recorded appropriately in the National GHG Inventory. This is important since it allows CCU to be recognised within the Party's efforts to reduce CO_2 emissions, and therefore count towards e.g. an NDC pledge.
2. Whether the CO_2 utilised in the product can be tracked and accounted for if it is subsequently emitted upon use (e.g. fuels) or upon disposal and degradation (e.g. chemical products). This is important to ensure that leakage is avoided.

In the context of these two questions, the 2006 GLs apply the following methods:

- For question (1), it states that CO_2 captured and utilised in chemical production should be deducted in a higher tier (Tier 3) emission factor calculation, taking account of both combustion and process sources of CO_2, and not be reported as CO_2 emissions from the process from which the CO_2 is captured (Vol. 3, Chapter 1.2.2). This implies that capture and use of CO_2 can be accounted for.
- On the other hand, for question (2), it states that quantities of CO_2 for later use and short-term storage should not be deducted from CO_2 emissions except when the CO_2 emissions are accounted for elsewhere in the inventory (e.g. urea and methanol production; Vol. 3, Chapter 1.2.2). Additionally, Vol. 1, Chapter 1.1, states that where CO_2 emissions are captured from industrial processes or large combustion sources, emissions should be allocated to the sector generating the CO_2 unless it can be shown that the CO_2 is stored in properly monitored geological storage sites.

These requirements implicitly mean that only geological storage of CO_2 is permitted as a permanent CO_2 abatement measure, and CO_2 utilisation can only qualify where effective accounting is in place that takes account of subsequent release to atmosphere, so as to avoid emissions leakage. This approach is only partly correct: the guidelines for Mobile Combustion (Vol. 2, Chapter, 3) do not contain methodologies that can take account of CO_2 uses in advanced fuels production, but the guidelines for Waste (Volume 5) should effectively take account of CO_2 released on disposal of CO_2-containing plastics such as polycarbonate. Capture and use for mineralisation is not considered within the 2006 GLs.

In general, it is apparent that the current IPCC Guidelines have not made a detailed consideration of the full implication of CCU technologies and their role in national GHG inventory compilation.

A third policy dimension to consider is the use of **project-based approaches and crediting**. This can potentially blend both the emission reduction at source and also the up- and downstream GHG benefits into a single CO_2 value. Doing so involves applying appropriate *boundaries* for the GHG inventory compiled for the project to ensure a full reflection of the total net GHG benefits being created. Such approaches can be less challenging than for product-based approaches, although to a certain extent they are quite similar in approach.

Problematically, to date there has been limited discussion of these policy choices in the literature, and as a consequence, thinking appears to be quite muddled on what advocates for CCU technologies want – and by extension, the relevant GHG accounting needs. This is not surprising – it is only over recent years that the rather disparate groups, including cement makers, building materials manufacturers, chemicals manufacturers and alternative fuel suppliers, have come together under the umbrella of "CCU", each with their own different backgrounds and interests. As can be seen in the literature, advocates of CCU technologies appear to be taking a wide-ranging approach, calling on policy-makers to, *inter alia*:

- Include CCU technologies in various schemes aimed at industrial CO_2 emission reduction, including the EU's GHG Emissions Trading Scheme, the US Carbon Sequestration Tax credit programme (45Q) and the US Clean Power Plan (e.g. SCOT Project, 2016; Global CO_2 Initiative/ICEF, 2016; Algal Biomass Organization, 2016); and,
- Standardise life-cycle analysis assessment in order to promote CCU products (e.g. Global CO_2 Initiative/ICEF, 2016).

But the purpose of these initiatives remains largely uncoordinated and without a clear strategy for promoting CCU as a GHG emission reduction technology in any jurisdiction. We anticipate that greater clarity on the appropriate approaches and choices will be forthcoming as we progress with this study.

The remaining sections of Part 2 consider the current policy and GHG accounting approaches applicable to CCU technologies, covering both facility-based and product-based accounting, as set out below.

6 FACILITY- AND PROJECT-BASED ACCOUNTING

The use of CO_2 capture is widely considered to deliver an emission reduction at source, and as such it lends itself to facility-level GHG emissions accounting where it directly reduces emissions from stacks. The same also applies for project-based accounting. In general, these type of approaches provide the basis for carbon pricing policies (emissions trading; carbon tax) where a cost is attached to emitting CO_2 to the atmosphere (which is avoided by CO_2 capture) or a price paid for the mitigation effort (e.g. through a crediting approach such as project-based schemes).

As mentioned previously, the key considerations in applying GHG accounting for CCU at a facility level are:

1. The scheme's accounting – or MRV – rules which must allow for captured CO_2 to be deducted from the facility/installation's GHG emissions inventory; and
2. That such rules take due account of the potential for emissions *leakage* to arise through the possibility of short-term *impermanence* of the emission reduction made at source.

In the case of (2), issues of permanence in CCS accounting and MRV have been addressed by establishing strict rules and regulations for CO_2 geological storage sites to ensure that they are appropriately selected, operated and closed to ensure long-term containment of injected CO_2. Adopting similar approaches for CCU applications will prove more challenging, however, since the CO_2 is integrated into products that will re-emit the CO_2 on use (i.e. fuels) and/or enter long, diverse and complex value chains which cannot be easily regulated and monitored to ensure permanence (e.g. chemicals). For these reasons, most schemes today do not recognise the application of CCU technologies as emission reduction at source, as described below.

6.1 Mandatory Reporting

The US, Canada and Australia all implement mandatory GHG emission reporting for large point-source fossil CO_2 emitters under Federal GHG Reporting Programs (US and Canada) and a National Greenhouse and Energy Reporting Act (Australia). The following section considers only the US as an example of treatment of CCU technologies under such schemes, although the other countries described follow similar rules.

6.1.1 US EPA GHG Reporting Program

The US Environmental Protection Agency (EPA) enforces the mandatory GHG Reporting Program (GHGRP) in the US (CFR 40 Part 98), which requires all facilities with emissions greater than 25,000 tCO_2/year to annually report emissions of relevant gases. Presently nearly 8,000 facilities in the US are reporting GHG emissions under the rule. Its purpose is to help the EPA better understand sources of GHGs to help make informed policy, business, and regulatory decisions. It can also provide a cornerstone of state-level enhanced actions under, for example, the Clean Power Plan.

The GHGRP has a wide number of subparts which set out the accounting rules applicable to different GHG emitting facilities. No subparts specifically relate to CCU activities, although it is treated within different subpart for different sectors, where relevant. For example:

- Subparts relating to the reporting of emissions from various industrial activities (e.g. Subpart C for *General Stationary Fuel Combustion Sources*, Subpart D on *Electricity Generation*, Subparts G, J, P, X etc. relating respectively to *Ammonia Manufacturing, Ethanol Production, Hydrogen Production, Petrochemical Production* etc.) all require that any CO_2 captured and transferred offsite be reported in accordance with *Subpart PP* (see below).
- Subparts involving chemicals production and on-site utilisation of captured CO_2 as a 'gaseous feedstock', such as ammonia or methanol production, require that the emissions from such utilisation be included in the facilities emissions calculation. Calculations are provided for its inclusion, and methods set down for measurement.
- *Subpart PP* applies to, *inter alia*, '*Facilities with production process units that capture a CO_2 stream for purposes of supplying CO_2 for commercial applications'*, and therefore applies to any CCU process. It requires these facilities to report the following:
    - Mass of CO_2 captured
    - Mass of CO_2 imported
    - Mass of CO_2 exported
    - The aggregated annual quantity of CO_2 that is transferred to the following end-use applications, if known:
        - Food and beverage
        - Industrial and municipal water/wastewater treatment
        - Metal fabrication, including welding and cutting
        - Greenhouse uses for plant growth
        - Fumigants (e.g. grain storage) and herbicides
        - Pulp and paper
        - Cleaning and solvent use
        - Fire fighting
        - Transportation and storage of explosives
        - Enhanced oil and natural gas recovery
        - Long-term storage (sequestration)
        - Research and development
        - Other.

In this way, the material flows associated with all applications involving CCU can generally be recorded within the ambit of the GHGRP. However, only geologic sequestration reported in accordance with *Subpart RR* (*Geologic Sequestration of Carbon Dioxide*) qualifies as an emission reduction activity and is eligible for Sequestration Tax Credits (45Q) and the EPA's Clean Power Plan (CFR 40 Part 60) and new Carbon Pollution Standards for New, Modified or Reconstructed Power Plants (CFR 40 Parts 60, 70, 71 *et al.*).

6.2 Emission Trading

Emissions trading allocates firms or other entities the right to emit within a given emissions constraint through the use of allowances which can be subsequently traded. The most common form of emissions trading is the cap-and-trade emissions trading scheme (ETS), which places an absolute limit on emissions – through the cap – and aims to drive least-cost emissions reductions through allowance trading. Over the past three decades, emissions trading has evolved into a major policy instrument for pollution control. As well as the development of major regional, national and sub-national ETSs, project-based schemes ("offsets") allow for emissions trading at the international level (e.g. through the Clean Development Mechanism, CDM) – as well as the regional, national and sub-national level, on both a compliance and voluntary basis.

6.2.1 EU GHG Emissions Trading Scheme

The European Union, by way of Directive 2003/87/EC, implements a GHG emissions cap-and-trade scheme across the EU-28 members plus four non-EU countries (the "EU ETS"). It covers more than 11,000 large GHG emitting 'qualifying' installations such as power stations, cement plants, steel works etc. Affected entities must surrender EU Allowances (EUAs) each year equal to the GHG emissions from their qualifying installations in the previous calendar year. The EUAs are auctioned by the European Commission, although certain trade-exposed sectors also receive a free allocation against a benchmark. The scheme is currently in Phase III, running 2013-2020.

Regulation No. 601/2012 on monitoring and reporting (the "MRR"; European Commission, 2012) sets down MRV rules for the calculation of annual GHG emissions from qualifying installations in Phase III of the scheme. These allow for captured CO_2 that is transferred out of a qualifying installation to be deducted from its GHG inventory, absolving its operator of the requirement to surrender allowances for that quantum of CO_2 that was captured and not emitted. As such, the EU ETS provides an incentive for CO_2 capture. The MMR, which was revised for Phase III, also specifically restricts the types of CO_2 transfers that can take place from an installation, limited to transfers only to another EU ETS-qualifying installation that is for the purpose of injection and geological storage. This change was introduced in 2012 to *'close loopholes'*[1] in the old measurement guidelines used in Phases I and II of the scheme. As a result, transfers of CO_2 for other purposes, such as utilisation in product synthesis, may not be subtracted from the installations GHG inventory.

This implicitly means that the capture and transfer of CO_2 for the purpose of CCU is not recognised in the EU ETS Phase III, and therefore any entity capturing and utilising CO_2 will be liable to surrender EUAs equal to the amount captured and utilised. Consequently, there is no incentive available for CCU under the EU ETS today, and no accounting or MRV rules have been developed specifically for CCU technologies. Nevertheless, there is scope for changes in this requirement as acknowledged in the preamble of the MRR, recital 13, where it is suggested that this development should not *'…exclude future innovations'*. This can be taken to mean that it is possible to opt-in new activities/technologies involving approaches such as CCU under Art. 24 of the ETS Directive (2003/87/EC), subject to the submission of appropriate MRV guidelines by interested member state governments. This would take place through a "comitology" process under Art. 23 of the ETS Directive, and has been applied before for CCS and N_2O emissions.

Very recently the legality of the limitations in the MRR on transferred CO_2 has been challenged in the European Court by a German calcinated lime manufacturer (Schaefer Kalk GmbH & Co). The company's calcinated lime production site is a qualifying installation within the EU ETS, although some of its CO_2 is captured and supplied it to a neighbouring precipitated calcium carbonate (PCC) production site that is not a qualifying installation under the EU ETS. Consequently, under the MRR, Schaefer Kalk had to include the transferred CO_2 within its GHG inventory under the

[1] See recital 13 of the preamble

EU ETS, even though it was transferred outside for PCC making. The European Court, on 19 January 2017, ruled in favour of Schaefer Kalk by concluding that the limitation of including within the facility's GHG inventory '*the CO_2 transferred to another installation for the production of PCC in the emissions of the lime combustion installation, regardless of whether or not that CO_2 is released into the atmosphere'* is "invalid".[1] As such, the MRR will need to be modified in the near future to appropriately account for such situations where CO_2 is transferred and utilised.[2]

Additionally, in early 2017 the European Parliament put forward its position on revisions to the EU ETS for Phase IV of the scheme (2021-2030), recommending that Directive 2003/87/EC implementing the EU ETS be modified so that, *inter alia*:

> *'An obligation to surrender allowances shall not arise….**in respect of emissions verified as captured and/or re-used in an application ensuring a permanent bound of the CO_2, for the purpose of carbon capture and re-use**'*[3]

During the trilogue negotiations in the latter part of 2017 between the European Commission, the European Parliament and the European Council, this amendment was not agreed, however, meaning CCU remains excluded from the EU ETS to at least 2030, albeit still possible through amendment of the MRR as described above. This was because the European Commission concluded that:

> *'Such* [CCU] *technologies are currently insufficiently mature for a decision in their future regulatory treatment* [and that it] *undertakes to consider their regulatory treatment in the course of the next trading period* [i.e. to 2030].*'* [4]

The provisional agreement for CCU within the revised EU ETS Directive is now therefore limited to eligibility under the EU ETS *Innovation Fund* ('NER400+'), where the technology is not yet commercially available, and:

> *'…contributes substantially to mitigate climate change, as well as products substituting carbon intensive ones produced* [in sectors covered by the EU ETS]…[and]…*shall deliver a net reduction in emissions and ensure avoidance or permanent storage of CO_2.'* [5]

It is also useful to note that the EU SCOT Project consortium (see Section 3.5) prepared a position paper on the role of the EU ETS in incentivising CCU (SCOT Project, undated). It proposed that mineralisation is the only the viable long-term storage route that could qualify for the EU ETS, subject to meeting certain CO_2 storage requirements such as longevity of the product. It also suggests that CCU processes that temporarily store CO_2 but substitute other

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[1] Judgment of the Court (First Chamber) of 19 January 2017. Schaefer Kalk GmbH & Co. KG v Bundesrepublik Deutschland. Case C-460/15

[2] Although the authors understand that this will likely be limited to cases where CO_2 is transferred for the purposes of PCC making

[3] Bold text outlines the proposed amendment to Article 12, para 3a. Amendments adopted by the European Parliament on 15 February 2017 on the proposal for a directive of the European Parliament and of the Council amending Directive 2003/87/EC to enhance cost-effective emission reductions and low-carbon investments.

[4] Statement from the European Commission at the Environment, Public Health and Food Safety Committee Trilogue, 28/11/2017

[5] Agreed amendments to Article 10(c) of Directive 2003/87/EC, as detailed in Provisional Agreement Resulting from Interinstitutional Negotiations by the Committee on the Environment, Public Health and Food Safety, 22/11/2017, page 34

fossil-based products should not be included within the scope of the EU ETS until a *'transparent, robust and comparable LCA analysis that could be scrutinised by an EU-ETS body'* is agreed. It also notes the risk of double counting of up- and downstream mitigation effects through this type of approach and the possible interactions with other polices such as the RED and FQD (see Section 7.1.3 below), and recommends that '*Research be undertaken into the challenges of determining avoided emissions so that findings may be considered at the 2025 mid-term review of the EU-ETS*'.

6.2.2 California Emissions Trading Scheme

The California Assembly Bill (AB) 32 – the *Global Warming Solutions Act* – set down the basis for a GHG cap-and-trade scheme in the US State of California. It applies to a range of activities including power plants, refineries, cement kilns and various other industrial plants that emit >25,000 tCO_2-e/year in the state, covering around 350 installations.

The scheme involves the use of auctioning and free allocation to distribute the trading units (California GHG Allowances) in the cap. It includes provisions for linkages (none are yet established) and allows the use of offsets from various domestic schemes, such as Forest and Livestock Projects, as well as projects developed by Air Resources Board (ARB)-approved Offset Project Registries: currently the American Carbon Registry (ACR) and the Climate Action Reserve (CAR). Credits from these registries must be converted to ARB-approved units for use in the ETS, which restricts the type of ACR and CAR offset projects eligible in the scheme (e.g. CCS).

MRV rules for the cap-and-trade scheme are set out in California Code or Regulation, Title 17, Division 3, Chapter 1, Subchapter 10, Article 2: *Mandatory Greenhouse Gas Emission Reporting*. Presently, emission reductions through the use of CCS are not allowed under the scheme. as the Reporting Guidelines to not contain quantification methodologies for CCS. However, this may change soon since the ARB is now developing a quantification methodology. As with other ARB quantification methodologies, the CCS quantification methodology may be adopted for use in the Cap-and-Trade and Low Carbon Fuel Standard programs (Air Resources Board, 2017a; see Section 7.1.2).

For CCU, the latest requirements for 'Carbon Dioxide Suppliers' requires reporting following *Subpart PP* of the GHGRP, as described above. No specific provisions are included for CCU technologies, and as such, CO_2 utilisation does not qualify as an emission reduction technology under the scheme.

6.3 Project-based schemes ("offsets")

6.3.1 Clean Development Mechanism

The UN Clean Development Mechanism (CDM) is a project-based scheme that allows emission reduction credits – Certified Emission Reductions (CERs) – to be generated for projects that reduce emissions in developing countries. At a project level, specific Approved Methodologies (AMs) must be developed according to the CDM modalities and procedures (CDM M&Ps) that set out the project-type specific GHG accounting rules, the basis for calculating the CERs generated by a project.

There are currently two approved CDM methodologies relating to CCU, namely:

- *AM0027: Substitution of CO_2 from fossil or mineral origin by CO_2 from renewable sources in the production of inorganic compounds*. The methodology is applicable generally to industrial production/manufacturing processes of inorganic compounds where fossil or mineral sources of CO_2 are presently used as an input and where renewable sources of CO_2 (i.e. CO_2 from the processing of biomass) are available as a substitute input in the project activity case (UNFCCC, 2011).
- *AM0063: Recovery of CO_2 from tail gas in industrial facilities to substitute the use of fossil fuels for production of CO_2*. The methodology is applicable to projects that reduce emissions associated with conventional CO_2 production process by means of extracting CO_2 from the tail gas or the intermediate gas produced at an industrial facility, e.g. hydrogen production within a refinery. The off-gas, produced as a result of the extraction of CO_2 from the tail gas or the intermediate gas, is supplied back to the industrial facility where it is either utilised as fuel or flared (UNFCCC, 2006).

In both cases, the emissions benefits arise from substitution of fossil-based CO_2 production for the purposes of commercial CO_2 utilisation: any emissions reductions accounted for apply therefore to the production of CO_2 only, and *not* those scenarios under which a CO_2-based fuel or product may or may not displace a more carbon-intensive alternative.

Under AM0027, the project activity may result in either reduced net CO_2 emissions to the atmosphere or carbon sequestration by substituting CO_2 from fossil or mineral origin with CO_2 that originates from the processing of biomass as input for the production process of inorganic compounds. In their final use phase, the inorganic compounds may either (i) thermally dissolve or (ii) not dissociate:

(i) Assuming that the inorganic compound molecules thermally dissolve in the final use. Hence, if a project activity uses renewable CO_2 instead of non-renewable CO_2 of fossil or mineral origin, emissions of non-renewable CO_2 during the final use of the compound are avoided.

(ii) On the other hand, in the case the inorganic compound molecules do not dissociate during the final use, the result of the project activity is carbon sequestration, because CO_2 is continuously sequestered from the atmosphere by the production of inorganic chemicals. Hence, the project activity leads to the permanent removal of CO_2 from the atmosphere (or "negative" emissions).[1]

Both methodologies require the consideration, and where relevant the calculation, of *leakage* emissions which are defined under the CDM as:

> "*…the net change of anthropogenic emissions by sources of greenhouse gases which occurs outside the project boundary, and which is measurable and attributable to the CDM project activity*" (UNFCCC, 2005)

[1] It is important to note that the main objective of the project activity is not to sequester CO_2 from the atmosphere. The inclusion of sequestration within the AM is to demonstrate that, even in the case that some portion of the chemical does not dissociate during the final use phase, the activity continues to lead to emissions reductions.

Under AM0027, leakage emissions are considered to be zero if the residual CO_2 from the processing of biomass was already produced but was not used before the project activity, so that no diversion of CO_2 from other applications is due to the project activity. Leakage emissions under AM0063 may arise in the case that the project facility displaces production of CO_2 from a new CO_2 production plant, or from several existing or new CO_2 production plants, that would have been constructed in the absence of the project activity to meet the growing demand of the national or regional market. In these cases, the share of non-conventional CO_2 production being displaced by the project must be accounted for in determining leakage emissions.

6.3.2 Japan's Joint Crediting Mechanism

Japan's Joint Crediting Mechanism (JCM), formerly the Bilateral Offset Crediting Mechanism (BOCM), shares many features of the CDM. Project methodologies, accounting rules and guidelines are developed by the JCM Joint Committee, which also acts as the mechanism's secretariat. One of several differences between the two mechanisms is that methodologies approved under the JCM are more streamlined than those developed under the CDM (e.g. making greater use of conservative default factors).

Since its formation in 2011, Japan has entered into JCM agreements with 16 host countries and, at present, 39 approved methodologies are registered under the JCM. Projects undertaken to date have typically focused on lower-cost abatement opportunities applying well-established mitigation technologies, such as energy efficiency, anaerobic digestion and solar PV. There are currently no known projects registered or under development applying CCU technology.

6.3.3 American Carbon Registry

The American Carbon Registry (ACR) was established in 1996 as the world's first private voluntary GHG registry. As of February 2017, 23 project methodologies have been approved by the ACR covering the energy, transport, industry, waste and agriculture sectors, with a further 6 currently undergoing technical review. Although CCS and EOR have been included, no methodologies include CCU technology.

The rulebook for the ACR is provided by the American Carbon Registry Standard (version 4.0, updated January 2015).[1] The ACR Standard defines eligibility requirements for new project methodologies as well as GHG accounting requirements, many of which mirror the CDM. ACR eligibility criteria do not exclude the use of CCU technology *a priori*, subject to various requirements around boundary definition, additionality and conservativeness – as well as more project-specific requirements aimed at reducing the potential for double incentives to occur.[2] The ACR also contains provisions to address permanence, with potential risk mitigation tools including the use of a credit 'buffer pool' and insurance products (ACR, 2015).[3]

[1] Version 4.0 is currently being updated; a draft Version 5.0 is open for public consultation until 20 March 2017.
[2] For example, for any project involving renewable energy generation within the project boundary, the project is only eligible if the renewable energy has not been counted toward a mandatory Renewable Portfolio Standard (RPS) obligation or claimed Renewable Energy Credits (RECs), unless regulations in the relevant jurisdiction clearly allow separation ("unbundling") of RECs and GHG attributes.
[3] These were developed in support of the inclusion of geological sequestration as an ACR project methodology.

6.3.4 Climate Action Reserve

The Climate Action Reserve, previously named the California Climate Action Registry, is focused on developing standardised GHG reduction project protocols, serving as a registry for GHG reduction projects, and tracking GHG offsets through a publicly accessible database. It does not currently include any CCU-related protocols.

6.3.5 Alberta Emissions Offset Registry

The purchase of Alberta- based carbon offset credits is one of the four compliance options for regulated entities under the Specified Gas Emitters Regulation in Alberta. CCU technologies are currently not included within the registered protocols although could be included, subject to a new protocol being developed and approved under the scheme.

6.3.6 Verified Carbon Standard

The voluntary-based Verified Carbon Standard (VCS) list of methodologies does not currently include any activities involving CCU technology. CCU could be included, subject to a new methodology or methodologies being developed and approved under the standard.

6.3.7 Gold Standard

The Gold Standard is a voluntary standard for creating high-quality emission reductions projects under the CDM, Joint Implementation and voluntary carbon market. The Gold Standard accepts all methodologies approved by the CDM that meet the Standard's own scope and eligibility criteria. In addition it has developed 16 Gold Standard project methodologies, none of which apply to CCU technology.

6.4 Other GHG trading schemes

A detailed review of other nascent emissions trading schemes in the Republic of Korea and China has not been conducted, but it is reasonable to assume that these jurisdictions have yet to make detailed consideration of the role of CCU within their programmes.

6.5 Other types of carbon emission regulation and pricing

6.5.1 US EPA Clean Power Plan

The EPA enforces the Clean Power Plan (CFR 40 Part 60), which aims to reduce carbon pollution from power plants across the US, and includes various elements such as Carbon Pollution Standards for New and Modified Power Plants, and the establishment of state-wide emissions goals in various forms. For the latter, states must develop and implement plans that ensure power plants in their state achieve the interim (period 2022-2029) and final (2030) performance rates.

In developing and implementing plans, states can consider the utilisation of a number of technology options, including the use of CCS and CCU. In the context of the former, the MRV for CCS is managed under existing rules within the GHGRP, namely *Subpart RR* as mentioned above. For the latter, the GHGRP does not contain any existing MRV rules that could be applied to CCU to account for the level of emission reductions that can be achieved. As noted by the EPA:

> *'…consideration of how these emerging* [CCU] *alternatives could be used to meet* CO_2 *emission performance rates or state* CO_2 *emission goals would require a better*

understanding of the ultimate fate of the captured CO_2 and the degree to which the method permanently isolates the captured CO_2 or displaces other CO_2 emissions from the atmosphere.' (Environmental Protection Agency, 2015, p. 64884)

It also, however, stated that it is *'committed to working collaboratively with stakeholders to evaluate the efficacy of alternative utilization options, to address any regulatory hurdles, and to develop appropriate monitoring and reporting protocols…'* (*ibid)*. In the meantime and until further guidance is issued by the EPA, states wishing to allow affected power plants to utilise these options to meet their performance rates must:

'...include analysis supporting how the proposed qualifying CCU technology results in CO_2 emission mitigation from affected EGUs [electricity generating units] *and provide monitoring, reporting, and verification requirements to demonstrate the reductions. The EPA would then review the appropriateness and basis for the analysis and the verification requirements in the course of its review of the state plan'* (*ibid.*)

As a consequence, efforts are being made within the US to consider the scope and approaches available to support these requirements (and also for Sequestration Credits under 45Q – see below). Partly this is being led by the NETL with a project that began in 2016.

6.5.2 US Carbon Sequestration Tax Credit (Section 45Q)

Presently in the US, CCS and EOR operators are eligible for a tax credit of up to US$20 tCO_2 captured and stored from electric power plants under the Internal Revenue Code Section 45Q.

In July 2016, Senators Heitkamp and Whitehouse proposed various amendments to Section 45Q by way of the Carbon Capture Utilization and Storage Act (S. 3179, 2016). The Carbon Capture and Utilization Act has now been repackaged as the FUTURE [Furthering carbon capture, Utilization, Technology, Underground storage, and Reduced Emissions] Act (S. 1535, 2017-2018), which proposes extension fo 45Q credit to cover 'utilization', referring to:

> *'the fixation of such qualified carbon dioxide through photosynthesis or chemosynthesis, such as through the growing of algae or bacteria, the chemical conversion of such qualified carbon dioxide to a material or chemical compound in which such qualified carbon dioxide is securely stored, or the use of such qualified carbon dioxide for any other purpose for which a commercial market exists'* [1]

As well as extending the scope of the tax credit to various forms of CCU (not just enhanced oil recovery using CO_2), the FUTURE Act includes provisions to increase the level of tax credit from US$5 to 10 per tonne sequestered to an amount increasing linearly over 12 years from around US$12-22 up to US$50 per tonne.

It is proposed that measurement of utilisation under 45Q will need to be made by '*analysis of lifecycle greenhouse gas emissions*' as well as other aspects that may be proposed by the Secretary of the Treasury in consultation with the DOE and EPA.[2] Presently work is ongoing

[1] S. 1535, Section 5(A)
[2] S. 1535, Section 5(B)

within NETL to consider approaches to life-cycle GHG accounting, and challenges can be expected when it comes to enforcement.

The proposed FUTURE Act has yet to be approved by the Senate, although it has bipartisan support from 24 Senators in the Upper House and can be expected to enter in force in due course.

7 PRODUCT-BASED ACCOUNTING

Project-based life-cycle GHG accounting methods have been employed to quantify and reward the GHG benefits of certain products ahead of others under various policy instruments and measures in different jurisdictions across the world. The relative merits and drawbacks of such approaches were discussed in Section 5, and as a result of these challenges, such approaches are limited in scale, and typically applied only to fairly homogeneous, standardised, simple products such as fuels.

The three main areas potentially relevant to CCU-derived applications and products are:

1. *Low-carbon fuel standards*. These are applicable for measuring and rewarding the full life-cycle GHG benefits of CO_2 to fuels pathways;
2. *Self-certification and voluntary declarations*. These can be used by CCU-based producers to communicate GHG benefits to policy-makers, competitors and the public. They are applicable to all CCU technology pathways;
3. *Ecolabelling*. This type of approach involves characterising the environmental – including GHG – benefits of certain products to attain an official standard label or logo, as issued by various scheme operators. The logo may be used on the product and associated marketing materials to communicate its benefits and distinguish it from others on the market.

Experiences with these schemes in the context of life-cycle GHG accounting for CCU technologies are described further below.

7.1 Low carbon fuel standards

A low-carbon or renewable fuel standard is a policy instrument that implements an obligation on fuel suppliers to reduce the full life-cycle GHG intensity of its portfolio of fuels supplied into a market (portfolio standard). The approach leads to the substitution of conventional petroleum-derived products with lower GHG intensity fuels. The obligation is increased over time, and can usually be met through either increasing the supply of low carbon fuels and/or the trading of certificates of origin of low-carbon fuels in order to help balance supply and demand across entities. To date, these schemes have generally been designed to promote the uptake of biofuels, as well as alternatives such as compressed natural gas (CNG) and liquefied petroleum gas (LPG).

The key method used to ensure the effectiveness of the policy is the use of life-cycle GHG emissions accounting to measure the relative GHG intensity of different fuels across their entire life cycle ("well-to-wheel" GHG intensity). Consequently, such schemes are backed up by detailed rules on the calculation of life-cycle GHG intensity to ensure that the fuels being promoted genuinely have a lower GHG emission intensity than petroleum-derived alternatives they are seeking to displace.

A discussion of the main LCFSs in place around the world, and their treatment of CO_2 to fuels pathways – both practical experience and potential application – is provided below.

7.1.1 US Federal Renewable Fuel Standard

The Renewable Fuel Standard (RFS) was introduced in the US in 2005, requiring a certain volume of renewable fuel to replace or reduce the quantity of petroleum-based transport fuel, heating or jet fuel supplied to the market. It presently covers only the following category of renewable fuels:

- Biomass-based diesel
- Cellulosic diesel
- Advanced biofuel
- Total renewable fuel.

Producers of these fuels are able to generate Renewable Identification Numbers (RINs) for the produced fuel, which in turn can be traded with compliance entities – refiners and importers of fuel – towards compliance with their Renewable Volume Obligations (RVO). Trading is accomplished through the EPA's Moderated Transaction System, rather than on an open market.

The RFS applies only to biomass based fuels, and therefore only CCU-derived fuels involving algae production can qualify under the scheme as 'Biomass-based diesel' products or 'Advanced biofuel'. For fuels not already pre-qualified, producers must petition to the EPA for approval as a qualifying fuel pathway by providing information and data on: (1) feedstock; (2) production process; and, (3) fuel type employed. The package submitted to the EPA is analysed by the EPA through an assessment of the life-cycle GHG reductions. To gain qualification the data must show that it achieves a reduction in GHG emissions compared to a 2005 petroleum baseline, according to the following thresholds:

- Biomass-based diesel must meet a 50% lifecycle GHG reduction;
- Cellulosic biofuel must be produced from cellulose, hemicellulose, or lignin and must meet a 60% lifecycle GHG reduction;
- Advanced biofuel can be produced from qualifying renewable biomass (except corn starch) and must meet a 50% GHG reduction;
- Renewable (or conventional) fuel typically refers to ethanol derived from corn starch and must meet a 20% lifecycle GHG reduction threshold.

Two algae-based fuel producers that are utilising CO_2 (Algenol Biofuels Inc. and Joule Unlimited) have successfully petitioned for qualification under the scheme as 'Advanced biofuels'. Both firms were able to show that ethanol produced from cyanobacteria (Algenol and Joule), and/or by extraction from biomass (Joule), and involving the use of 'waste' CO_2, met the 50% emission reduction threshold.

The EPA uses a proprietary method for calculating the life-cycle GHG emissions, and at the current time it has not been possible to gain a deeper understanding of the effects of 'waste' CO_2 utilisation on the overall life-cycle GHG emissions of the fuels under consideration. This will be made in later stages of the study.

7.1.2 California Low Carbon Fuel Standard

The California Low Carbon Fuel Standard (LCFS) came into force in 2011 with the aim of incentivising low-carbon fuels as an alternative to petroleum and diesel. The LCFS is administered by the California ARB and requires oil refineries and distributors to ensure that the mix of fuel they sell into the Californian market for transport purposes meets set targets for GHG emissions per unit of fuel energy sold. The regulation intends to meet the required reduction of at least 10% in the carbon intensity of California's transport fuels by 2020 through steadily increasing targets.

The calculation of GHG emissions associated with the supply of transport fuels is based on the use of carbon intensity reference values for different 'fuel pathways' calculated and imposed by ARB. These values consist of the sum of the GHG emitted throughout each stage of a fuel's production and use (life cycle). Each intensity value is expressed as the amount of life cycle GHG emissions per unit of fuel energy in grams of CO_2-equivalent per megajoule (gCO_2e/MJ); these include both the direct effects of producing and using the fuel as well as indirect effects associated with how the fuel impacts other products and markets.

ARB uses the California-modified GREET[1] (CA-GREET) model (version 2.0, updated in September 2015) to generate the carbon intensity values. All regulated parties and other entities affected by the LCFS must conduct their life-cycle analyses using CA-GREET. GREET is a publicly available spreadsheet model developed at the Argonne National Laboratory (ANL) and has become a standard tool for LCA of transport fuels in the US. GREET calculates emissions of three GHGs (CO_2, CH_4 and N_2O) with global warming potential values used to aggregate the three GHG emissions into a single CO_2e value. Volatile organic compounds (VOC) and carbon monoxide (CO) are also counted, in their fully oxidised forms as CO_2. The GREET model includes provision for a wide range of feedstocks, fuels, and vehicles.

The certified fuel pathways included in CA-GREET cover:

- "Tier 1" (first-generation) fuels – covering 23 common conventionally produced fuels e.g. starch- and sugar-based ethanol, biodiesel, renewable diesel, CNG, LNG; and
- "Tier 2" (next-generation) fuels – covering cellulosic alcohols, hydrogen, drop-in fuels, etc. or first-generation fuels produced using innovative production processes

The different categories apply different calculation methodologies. The wide range of certified values reflect, *inter alia*, variations in feedstock types, origin, raw material production, processing efficiencies and transportation. As of 15 February 2017, the LCSF included a total of 323 certified fuel pathways and associated carbon intensity values (Air Resources Board, 2017b).

Regulated entities can make an application to ARB requesting a new fuel pathway to receive a carbon intensity score. They can apply for either Tier 1 or Tier 2 treatment, with the latter subject to increased process and evidence scrutiny. The LCFS specifically exempts a number of lower-carbon fuels, such as electricity and hydrogen, because they meet the carbon intensity targets through to 2020. Providers of these fuels, if they choose not to participate in the LCFS program, have no obligations for these fuels under LCFS. However, LCFS allows these fuel providers to opt-in to the program. The LCFS fuel pathway application and certification process requires that certain documents and supporting evidence associated with the LCFS pathway be

[1] Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model

submitted through the ARB's Alternative Fuel Portal (AFP) website; Tier 2 applications must be made available for public comment or inspection.

CO_2-derived fuels are not currently reflected in the list of approved fuel pathways, and at present there are no known applications relating to CCU technology. It should be noted, however, that during the development of the LCFS, the ARB envisaged biofuels-from-algae technologies to enter the LCFS after 2020 (Air Resources Board, 2009). At present, producers of Tier 1 fuels may qualify for Tier 2 by utilising low-carbon forms of process energy, using unconventional, low carbon feedstocks, or using a method of CCS; these applicants do not need to demonstrate a specific reduction in carbon intensity. Various rules that may be potentially applicable to calculating GHG intensity for CO_2 to fuels pathways are also described under the current LCFS rules. For example, electricity from a renewable energy source utilised in a fuel pathway may only be included in the intensity value determination if the energy from that source is directly consumed in the production process.[1] Notwithstanding such guidance, the treatment of new CCU fuel pathways within the LCFS GHG accounting process remains to be determined.

7.1.3 EU Renewable Energy Directive and Fuel Quality Directive

The EU's 2009 Renewable Energy Directive (RED), and the supporting Fuel Quality Directive (FQD) and its revisions, acts to implement a portfolio standard for transport fuel suppliers, based on reaching a target of 10% renewable transport fuel use in the EU by 2020. The FQD, Annex IV, and Directive 2015/652 on other fuels including other energy from non-biological sources (the "iLUC Directive"), provides the basis for methodologies by which the life-cycle GHG intensity of different fuels must be calculated.

Using these methods, the FQD requires fuel suppliers in the EU to report annually the GHG intensity of fuel and energy supplied and used within each Member State according to:

- the total volume of each type of fuel or energy supplied, indicating where purchased and its origin; and
- life cycle GHG emissions per unit of energy.

The 10% reduction target is made up of various components:

- a 6% reduction of the GHG intensity of fuels by 2020 compared to 2010;[2]
- an additional 2% from technologies capable of reducing life cycle GHGs (including CCS); and
- a further 2% through the purchase of certified emission reductions (CERs) from the fuel supply sector.

[1] No indirect accounting mechanisms, such as the use of Renewable Energy Certificates (RECs), can be used in determining the intensity value from electricity consumption. The applicant must provide evidence that the generation source is dedicated, generally by showing that the source is onsite/co-located, or was developed by the fuel producer with the sole intention of providing renewable power to the fuel pathway.

[2] Eligible fuels must have a GHG intensity at least 35% lower than the fossil fuel comparator, increasing to 50% in 2017, and 60% in 2018 (for new installations). The "iLUC" Directive also revised these targets slightly and limited the share of biofuels from crops grown on agricultural land that can be counted towards the target to 7%. It also introduced a 0.5% target for Advanced Biofuels (e.g. from algae and waste).

As the RED 2009 defined energy from renewable sources – and therefore renewable fuel – as '*energy from renewable non-fossil sources, namely wind, solar, aerothermal, geothermal, hydrothermal and ocean energy, hydropower, biomass, landfill gas, sewage treatment plant gas and biogases*', it broadly excluded CO_2-to-fuel pathways since these constitute a fossil-fuel origin, with the exception of algae that may have been produced using captured CO_2.

However, revisions were made to both the RED and FQD in 2015[1] that allow for the use of '*renewable liquid and gaseous transport fuels of non-biological origin'*. This revision allows for CO_2-derived fuels to contribute towards the overall meeting of the 10% renewable transport fuel target by 2020. The accompanying Directive 2015/652 sets out rules for calculating the GHG intensity of other fuels, including energy from other non-biological sources (and therefore possibly CCU-derived fuels). The document did not clearly address methods for calculating the GHG emissions for 'energy from other non-biological sources', although it gave a mandate to the European Commission to establish default GHG emission factors for such fuels by the end of 2017. The Commission is currently consulting on the matter at the time of writing (until the end of March, 2017; European Commission, 2016f).

In addition, proposals for revisions to the RED could extend the qualifying renewable transport fuels to include '*waste-based fossil fuels*', defined as '*liquid and gaseous fuels produced from waste streams of non-renewable origin, including waste processing gases and exhaust gases*'. These revisions, if approved by the European Parliament and Council, will further broaden and strengthen the legal framework for promoting and incentivising fuels derived from CCU in Europe post-2020.

7.1.4 UK Renewable Transport Fuel Obligation (RTFO)

The UK introduced its RTFO on fuel suppliers in 2005, and it entered into force in 2008. It required transport fuel suppliers to ensure that at least 5% of all road fuels supplied is from sustainable renewable sources by 2010. It has since been subject to a number of amendments to, for example, modify the target and to bring it in line with the EU's RED targets, as described above.

Recently, the UK Department for Transport – responding to changes in the RED and FQD described above – has proposed the inclusion of Renewable Fuels of Non-Biological Origin (RFNBOs), such as '*hydrogen produced from electrolysis of water using renewable electricity; or methanol via catalytic fuel synthesis of renewable hydrogen'* (UK DFT, 2016). It also proposes that *'In order to ensure non-biological renewable fuels are sustainable we propose that they deliver at least the same minimum greenhouse gas savings as biofuels.'* Under these proposed amendments, CCU-derived fuels would have a clear role to play in meeting future renewable transport fuel supply obligations.

The proposal is currently subject to consultation alongside other reforms – and is also subject to some uncertainty due to the UK's policy to leave the EU before 2020.

[1] Under the so-called "iLUC" Directive. Directive 2015/1513.

7.2 Self-certification and voluntary standards

Several firms developing CCU technologies have had independent voluntary assessments made of the carbon benefits associated with their processes and products. These include, for example:

- Carbon Recycling International's (CRI) (Iceland) renewable methanol – marketed under the name *Vulcanol* – certified by SGS Germany GmbH according to the International Sustainability & Carbon Certification (ISCC) Plus standard, making it the first ISCC certificate for renewable fuels of non-biological origin;
- Newlight Technologies' (US) AirCarbon™ thermoplastic product awarded Bronze level Cradle to Cradle Certified™ Product Standard by third-party certification company MBDC; and,
- Covestro's[1] (Germany) production of CO_2-based polyols subject to detailed carbon life-cycle assessment (LCA) by RWTH Aachen University.

The resulting claims made by these and other firms are largely based on LCA-type analysis of GHG emission (and sometimes other) impacts.

For example, CRI reports that '*Vulcanol from our current production plant reduces carbon emissions by more than 90% compared to fossil fuels, in the complete product life-cycle, from extraction, production to end use*.' (CRI, 2017). The ISCC Plus standard describes a methodology for the calculation and testing of GHG emissions along the supply chain, and has been adapted to cover renewable fuels of non-biological origin (ISCC, 2012).[2] ISCC claim that '*the audit of CRI in Iceland has shown that the fuel is produced sustainably, with high greenhouse gas savings and […] without indirect land use effects*.' (SGS, 2013). Beyond the published headline figure of achieving a 90% emissions reduction, the results of the Vulcanol LCA – including any boundary and scope conditions, and data assumptions – are not publicly available.

Similarly, the scale of carbon benefits and/or certification requirements under the Cradle to Cradle Certified™ Product Standard awarded to Newlight Technologies' AirCarbon™ product have not been made publicly available.[3]

In contrast, the LCA undertaken by RWTH Aachen University for Covestro's production of CO_2-based polyethercarbonate polyols at its Dormagen site – as part of the Dream Production project[4] – have been presented in some detail (Von der Assen and Bardow, 2014). The cradle-to-gate system boundaries include polyol production and upstream processes including energy

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[1] Formerly, Bayer Material Science.

[2] The add-on to the requirements for the calculation of greenhouse gas (GHG) emissions (ISCC PLUS 205-01: "Greenhouse Gas (GHG) Emission Requirements") has been developed for the calculation and testing of GHG emissions along the supply chain. The add-on provides a methodology to calculate all relevant emissions from biomass production through different conversion processes to transport and distribution. ISCC indicate that companies that want to provide their customers with information on the greenhouse gas emissions of their products or supply chains can choose this add-on.

[3] The Cradle to Cradle Certified™ Product Standard applies five quality categories - material health, material reutilisation, renewable energy and carbon management, water stewardship, and social fairness. A product receives an achievement level in each category - Basic, Bronze, Silver, Gold, or Platinum - with the lowest achievement level representing the product's overall mark. Every two years, manufacturers must demonstrate good faith efforts to improve their products in order to have their products recertified.

[4] "Dream Production – CO_2 as building block for polymers" (033RC1005B) funded by the German Federal Ministry of Education and Research (BMBF).

sources and feedstock. The published LCA presents the boundary and data assumptions in some detail and concludes that compared to conventional polyether polyols, polyethercarbonate polyols with 20% CO_2 (by weight) can reduce GHG emissions by 11-19%, and save fossil resources by 13-16% (*ibid*).

Even a cursory review of such claims currently being made by CCU technology developers indicates a major lack of transparency and comparability in the existing use of certificates, standards and LCA analyses. For most claims, there is little or no publicly available information relating to the scope and boundaries, or the various assumptions used to undertaken the analyses – such as feedstock and energy inputs, raw material and product substitutions, or 'conventional' and/or fossil-fuel baselines used to undertake any comparisons. In addition, geographical and temporal benefits/effects are not typically reported – for example, where and to whom the carbon benefit is accruing, and over what timeframe (noting here the importance of the *permanence* issue in robust emissions accounting for many CCU technologies).

The current use of self-certification and voluntary standards has an important role to play in marketing CCU products and communicating their environmental benefits to consumers. However, they are not of a sufficient standard to be used in carbon pricing and other types of support schemes requiring robust and comparable accounting systems. Understanding the full life-cycle emissions impacts of CCU technologies has been noted as being especially important for validating policy support and guiding research (Global CO_2 Initiative/ICEF, 2016). Notwithstanding the 'quality' of specific standards or LCA methodologies currently available, their use for policy-making will therefore require additional efforts.

At present, the International Organization for Standardization (ISO) 14000 series establishes a standard framework and general procedure for performing LCA calculations and is widely accepted. However, even when using this framework, many other complications occur in practice (*ibid*). Because of these complications, LCA experts can come to very different conclusions about the overall emissions impact of the same or similar CCU technologies.[1] As governments and industry consider increasing policy support for CCU, ideally, they will need to compare and harmonise their approach to LCA as it applies to policy decisions (*ibid*). In this context, the *Global CO_2 Initiative* is currently *'planning to convene a global expert panel in an attempt to 'standardize' LCA analysis for CO_2U* [i.e. CCU] *technologies'* (*ibid*. pg. 48).

7.3 Eco-labelling

Ecolabelling (e.g. EU Ecolabel; The Blue Angel/Blau Engel in Germany) has been mooted as a possible way to recognise the GHG emission reduction benefits of CCU-derived products (JRC, 2013; El Khamlichi, 2016), but no work has so far been carried out in this area, and the potential benefits of doing so remain unclear. To date, CCU operators have preferred to take the self-certification option as described above.

[1] For example, a review of 16 individual studies of CCU technologies including mineral carbonation (mineralization), chemical production, biofuels production, and EOR found a wide range of results, whose variation is so big that it is difficult to draw conclusions about their relative emissions impact, or give guidance to policymakers (ICEF, 2016).

8 CONCLUDING REMARKS

This report provides a rapid assessment of the historical development (since around the mid-2000s) and current status of CCU technology across many parts of the world. The results allow a number of generalised conclusions to be drawn regarding the current technological, political and regulatory environment in which CCU technologies are developing today.

At a political and academic level, it is apparent that momentum for CCU has increased significantly over recent years. This may in part be a response to the difficulties faced in establishing CCS in in several parts of the world, most notably Europe. But it is also partly a response to the potentially wider benefits offered by CCU, in particular its fit to the 'circular economy' concept. In tandem with the growing momentum, various governments have mobilised reasonably large grant-based research and development funds for CCU technology since about 2009, including in the US (under ARRA) and the BMBF programme in Germany. These funding activities exceed US$200 million in grant support for at least 50 such activities. Other smaller-scale support has also been offered by the European Commission and the governments of the UK and France. Despite these efforts, uncertainty remains regarding the true potential of CCU technologies to deliver real, measurable, verifiable and scalable GHG emission reductions. This is largely due to a lack of transparency by operators regarding the energy and carbon balances of CCU processes, resulting in a significant asymmetry in understanding between policy-makers and developers.

More recently, a number of inducement prizes/Grand Challenges have been launched in the field of CCU, which are ongoing at the time of writing. These include the privately sponsored *Carbon XPrize* in the US and the European Commission's *CO_2 Reuse Prize*. These types of support measures are typically employed alongside R&D funding where there are a number of competing technologies that can potentially deliver similar outcomes, and where there is a lack of transparency about the real potential of differing approaches to achieve significant, commercially-viable and scalable benefits. They can also help to reduce the asymmetry in knowledge between researchers and policy-makers, as typically they require data and information to be collected and submitted in pursuit of the prize aim. Most of these programmes will conclude over the period 2019-2021, after which greater knowledge should be forthcoming regarding the potential of CCU technologies and their ability to reduce GHG emissions.

Notwithstanding the ongoing asymmetry of information and its potential resolution in the next few years through the prize programmes, the political momentum behind CCU technologies seems to be continuing unabated. Many of these efforts are focussed on bringing CCU technologies into the ambit of mainstream climate change mitigation policies, particularly alongside CCS. Presently, CCU technologies are largely excluded from such schemes, primarily due to concerns over GHG accounting and MRV in respect of the net GHG benefits they might deliver, and issues for boundary setting, emissions leakage and permanence in the accounting/MRV rules. For example, actions in Europe are seeking to ensure inclusion of CCU within the EU ETS and the RED within the next two to three years, and in the US, inclusion under the 45Q Sequestration Tax Credit scheme and the Clean Power Plan. These activities are seemingly backed up by influential corporate and academic groups such as the *World Economic*

Forum, which is supporting the Global CO_2 Initiative, and experts such as David Sandalow, Inaugural Fellow at Columbia University's Center on Global Energy Policy, former Under Secretary of Energy (acting) and Assistant Secretary for Policy and International Affairs at the US DOE, and Steering Committee member of the Innovation for Cool Earth Forum (ICEF). David Sandalow was a lead author of the ICEF CCU Roadmap that provided the ambitious estimate that the main product groups involved in CCU could utilise around 7 $GtCO_2$/year and create a market of over US$800 billion by 2030 (Global CO_2 Initiative/ICEF, 2016). David Sandalow and colleagues have recently published an updated CCU Roadmap v2.0, launched at COP23 in late 2017 – again under the auspices of the ICEF and sponsored by the Government of Japan (Global CO_2 Initiative/ICEF, 2017).

The actions at a political level and the R&D activities for CCU on the ground appear to be out of synchronisation. The number of commercial CCU project developments around the world today are limited, are often only viable in unique niche circumstances, and most technologies are at TRL5 or less. Realistically, these technologies can only be considered as mainstream climate mitigation tools if proven over the next 5-10 years. Moreover, there is genuine uncertainty about whether CCU technologies do actually deliver net GHG emission reductions, and whether they can be scaled up to create deep cuts in global GHG emissions over the medium term. These uncertainties are manifested in the forthcoming challenges that will be faced by regulators in trying to ensure that emission reductions policies into which CCU is trying to be 'mainstreamed' include sufficiently robust GHG accounting and MRV rules. These are necessary to ensure that emission reductions achieved by CCU, and the associated revenues, are effectively tracked and calculated according to the net GHG benefit delivered rather than claimed. Whilst there is undoubtedly strong low-carbon potential across the pool of emerging CCU technologies, the challenge will lie in appropriately promoting and rewarding the most viable and effective ones.

As such, the work programme envisaged within this project will provide a timely intervention to the knowledge base and ongoing political debate, and should help regulators to gain a clearer picture of the issues associated with GHG accounting and MRV for CCU technologies.

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