Evaluating technology options to mitigate greenhouse gas emissions

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

Synthesis of Research Findings

IEAGHG Technical Review
2018-TR01c
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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

Synthesis of research findings

FINAL REPORT

Carbon Counts Company (UK) Ltd

9 April 2018

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Our Ref: 083

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ACRONYMS AND ABBREVIATIONS

ACT	Accelerated Carbonation Technology
APCr	Air Pollution Control Residue
bbl	Barrel of crude oil
CCS	Carbon dioxide (CO_2) capture and storage
CCU	CO_2 capture and utilisation
CHP	Combined heat and power
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
COG	Coke oven gas
CRI	Carbon Recycling International
DOE	United States Department of Energy
EfW	Energy-from-waste
EOR	Enhanced Oil Recovery
ETL	Emissions-to-liquids
EtOH	Ethanol
EU ETS	European Union Emissions Trading Scheme
FGDr	Flue Gas Desulphurisation Residue
FQD	Fuel Quality Directive
ft	Feet
gal	Gallon
GHG	Greenhouse Gas
Gt	Gigatonne
H_2	Hydrogen
H_2S	Hydrogen sulphide
IBR	Integrated Biorefinery
ICEF	Innovation for Cool Earth Forum
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
kg	kilogram
kWh	Kilowatt-hour
l	Litre
LCA	Life-cycle assessment

MDEA	Methyldiethanolamine
MeOH	Methanol (CH_3OH)
MJ	Megajoule
mol	Mole (unit of substance)
MRV	Measurement, Reporting and Verification
MW	Megawatt
MWe	Megawatt equivalent
MWh	Megawatt-hour
NDC	Nationally Determined Contribution
NETL	United States National Energy Technology Laboratory
Pa	Pascal
PBR	Photo bioreactor
PDU	Process Development Unit
ppm	Parts per million
PSA	Pressure swing adsorption
R&D	Research and development
SCOT	"Smart CO2 Transformation" programme
SRCCS	Special Report on Carbon Dioxide Capture and Storage (IPCC)
t	Tonne
UNFCCC	United Nations Framework Convention on Climate Change
VCD	Vapour compression distillation
VCSS	Vapour compression steam stripping
W	Watt
WEF	World Economic Forum

PREFACE

The assignment “Greenhouse Gas Emission Accounting for Carbon Dioxide Capture and Utilisation Technologies” has been undertaken by Carbon Counts Company (UK) Ltd (“Carbon Counts”) for the IEA Greenhouse Gas R&D Programme (IEAGHG) over the period February 2017 to February 2018. The inputs of IEA GHG staff and members in supporting development of the project – in particular Tim Dixon and Jasmin Kemper – are gratefully acknowledged. The authors are also grateful to the following CCU operators for providing the support and information without which the analysis would not have been possible:

- Carbon Recycling International (CRI)
- Carbon8 Aggregates (C8A)
- Algenol Biofuels
- Cenovus Energy Inc.
- SaskPower

This report provides a synthesis of findings covering the body of research undertaken.

SUMMARY OF FINDINGS

A summary of the main findings of the research programme on greenhouse gas (GHG) emissions accounting for CO_2 capture and utilisation technologies (CCU) are as follows:

Momentum for CCU has increased significantly over recent years at a political, industrial and academic level. This may in part be a response to the difficulties faced in establishing CCS 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 fairly large grant-based research and development funds and prizes for CCU technology since about 2009. Various multi-year funding activities by governments around the world exceed US$200 million at the time of writing.

A number of funded CCU research, development and demonstration (RD&D) projects, and several ongoing commercial operations, are active around the world at the current time. Analysis suggests that around 200 CCU projects have been launched over the past 15-20 years or so, of which 113 are thought to be currently operating. Most are located in Europe (44%; predominantly Germany), the USA (33%) and Canada (10%). The majority of project activities are focussed on CO_2 to fuel pathways (43%) and chemicals production (35%), with the remainder involving CO_2 mineralisation.

Despite the various RD&D funding efforts, uncertainty remains regarding the efficacy of CCU technologies to deliver real, measurable, verifiable and scalable GHG emission reductions. This is in part due to a lack of transparency by operators regarding the energy and carbon balances of CCU processes, resulting in significant asymmetry in understanding between policy-makers and developers. It is also a result of the lack of consistency in accounting methods used by operators to report the GHG emissions and GHG benefits of their technology. Establishing guidelines that promote consistent GHG accounting methodologies for CCU should help to improve transparency, and several initiatives are ongoing in this context e.g. led by the *Global* CO_2 *Initiative*, and as prepared under this work programme.

Asymmetry of information notwithstanding, there is growing political pressure on regulators to integrate CCU into low carbon policies. There are several efforts 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 or measurement, reporting and verification (MRV) rules. For example, the European Parliament has sought to explicitly include CCU technologies within the EU's greenhouse gas emissions trading scheme (ETS) whilst modifications to the Renewable Energy Directive (RED) within the next two to three years will allow for fuels derived from waste CO_2 to be counted towards targets. In the US, CCU may soon be included under the 45Q Sequestration Tax Credit scheme (through the proposed FUTURE [Furthering carbon capture, Utilization, Technology, Underground storage, and Reduced Emissions] Act), as well as 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 the Innovation for Cool Earth Forum (ICEF).

Actions at a political level and the RD&D activities for CCU on the ground appear to be out of synchronisation. The number of commercial CCU project developments around the world today is limited, are often only viable in niche circumstances, and most technologies are at technology readiness level (TRL) 5 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 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 that recognise CCU include sufficiently robust GHG accounting and MRV rules. These are necessary to ensure that emission reductions achieved by CCU, and any 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 lies in appropriately regulating and recognising the most viable and effective ones.

Analyses of the energy and carbon flows across a selected number of commercial and demonstration scale CCU case studies showed that there is potential for GHG benefits to arise from CCU. Operators of all four case studies examined, namely Carbon8 Aggregates (C8A), Carbon Recycling International (CRI), Algenol and Boundary Dam-Weyburn, exhibited a deep understanding of the energy and CO_2 flows and GHG emissions associated with their technology, and several have had their GHG analyses and claims verified by third parties. In all cases the technology appears to be generating net GHG emission reductions when compared with a conventionally produced, functionally-equivalent product. Analysis suggests that net GHG benefits vary from around <0.5 to >2 tCO_2e per tonne CCU-derived product output across the different technologies. On the other hand, the achievement of net GHG benefits are highly predicated on several factors: firstly, most benefits accrue from assuming that the utilised CO_2 would be otherwise emitted to atmosphere; second, the particular circumstances where the CCU activity takes place. In the case of the latter, for example, the electro-intensive production process of CRI's emissions to liquids (ETL) technology means that GHG benefits are contingent on the availability of a reliable low-carbon electricity source at a suitable price. The scale-up potential of CCU may be constrained by such niche conditions and limit the ease of replicability for some technology applications.

Net GHG benefits arising from CCU technologies can only be fully assessed by taking a life cycle GHG accounting perspective. Many of the GHG emission reduction benefits of CCU are predicated on the 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, and the capture and supply of CO_2 from flue gases reduces point source emissions. On the demand side, the production of CO_2-derived chemicals and fuels can displace fossil-derived alternatives such as crude oil. 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 (a *permanence* issue). To address these questions, most observers advocate life cycle analysis (LCA), although common LCA methods have yet to be agreed, and are hampered by inconsistencies and gaps in the datasets typically employed by LCA practitioners.

The complexity of GHG accounting and net GHG benefit assessment can be reduced by employing a 'CO_2 capture benefit' method. The method developed and employed in this report is based on firstly, *systems expansion* to account for the capture of CO_2, and, subsequently, an *avoided burden* method to establish a consistent approach to accounting for the net GHG benefits arising from the CO_2 capture part of the CCU value chain. The CO_2 capture benefit essentially describes the rate at which CO_2 emissions are avoided for each tCO_2 captured, or in other words, the upstream CO_2 abatement effect embedded in each tCO_2 utilised downstream. This allows for gate-to-gate LCA comparisons between CCU- and conventionally-derived products, with the benefit of CO_2 capture transparently factored into the former. It is considered advantageous for several reasons, including *inter alia*, improving the transparency of GHG accounting methods, reducing complexity and methodological burden upon stakeholders, and transparently highlighting where and how overall net GHG benefits may be delivered by CCU.

Although the analysis provides new insights into CCU GHG accounting, it is partial since it considers only energy and carbon flows across the CCU life cycle and is based only on large demonstration/commercial-scale operations. This does provide a valuable building block from which to develop more comprehensive approaches, however. Operating case studies were specifically selected to avoid the pitfalls inevitably arising when attempting to model CCU technology performance; such estimates are predicated on making a large number of assumptions, which can lead to significant errors and uncertainty. It also means that the analysis focuses on intermediate products such as methanol and construction aggregates, and is undertaken on a cradle-to-gate basis. End-use was also included to address questions relating to permanence. Secondary processing and/or conversion to final products is excluded. In addition, life cycle GHG emissions embedded in various component processes are excluded: for example, materials consumption, water consumption and waste. This was due to a paucity of information. The results remain highly informative, however, since the calculated net GHG benefits presented show the "headroom" into which additional GHG emissions from these components would need to fill before a CCU-derived product becomes less beneficial for the climate than a conventionally-produced alternative. It also avoids the significant uncertainty that can arise from trying to estimate the GHG emissions embedded in these component activities. Other LCA studies of CCU suggest that these components can lead to wide variations in the results, which hamper interpretations about the underlying energy and carbon balances of the processes (e.g. Cuéllar-Franca and Azapagic, 2015).

Based on the approach taken in this research, CCU GHG accounting guidelines v1.0 have been prepared to facilitate improved transparency about CCU and emission reductions. The guidelines can assist in establishing systematic methods by which life cycle GHG emissions and net GHG benefits of CCU technologies can be made. They can also serve to stimulate further discussions and ongoing research relating to action being taken to appropriately regulate CCU.

The life cycle of CCU means that several factors must be kept in mind when designing appropriate policies and regulation. These include the point in the CCU life cycle where the greatest GHG benefits accrue (primarily capture), how any carbon price signal may be allocated among the actors involved across capture and use, whether double incentives are a problem or not, how double counting can be avoided, and how matters relating to permanence can be effectively remedied in cases where CO_2 is remitted upon use. For the latter, if the CCU-derived product is assumed to perfectly substitute a functionally-equivalent fossil derived alternative, the results suggests that permanence is not a particularly material consideration.

1 INTRODUCTION

1.1 Background

Interest from policy-makers, industry and academia in technologies that can utilise carbon dioxide (CO_2) to manufacture new products has grown dramatically over recent years. Looking back 12 years from today, such technologies – often referred to collectively as CO_2 capture and utilisation (CCU) technologies[1] – were 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*'. Similarly, the United States (US) government, through the Department of Energy (DOE) National Energy Technology Laboratory (NETL) also broadly 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, industrial and academic efforts to promote the greenhouse gas (GHG) 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[3] and Germany[4], 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);

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[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. A detailed technical review of

[2] Technical Summary, p. 41

[3] American Recovery and Reinvestment Act (ARRA) funding of around US$120 million

[4] Federal Ministry of Education and Research (BMBF), Research for Sustainability (FONA) funding of around €100 million on "Technologies for Sustainability and Climate Protection – Chemical Processes and Use of CO_2"

- 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.

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.

Problematically, despite the increasing interest, uncertainty remains regarding the technology's true potential to contribute towards wider GHG emission reductions goals. A range of views have been expressed in these contexts, but on the whole it remains largely speculative and unproven at the time this research programme commenced. Consequently, it has historically proved difficult to provide firm opinions on whether CCU technologies can make a meaningful and lasting contribution to tackling climate change.

A 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. This issue was noted by the IPCC in the 2005 SRCCS (Metz *et al.*, 2005) where it was observed that: *'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 the authors' knowledge, such detailed studies have, at best, only partially been carried out (or at least disclosed in the public domain) and are heavily reliant on assumptions made in the analysis or have been hampered by the inconsistencies in the literature reviewed (e.g. Global CCS Institute, 2011; ADEME, 2014; von der Assen, 2015; Cuéllar-Franca and Azapagic, 2015).

This study set out to address this knowledge gap.

1.2 Purpose, Scope and Approach

Based on the backdrop outlined, the overall aim of the study was to gain a better understanding of the potential of CCU technologies to contribute towards climate change mitigation objectives (i.e. by reducing emissions of anthropogenic CO_2 to the atmosphere). The objective was achieved through a multi-staged research process covering the following:

Activity 1 – Characterising CCU technologies and emission reduction pathways
Activity 2 – CCU facility-level GHG emissions (case studies)
Activity 3 – Developing a composite life-cycle GHG emission profile for CCU activities
Activity 4 – Development a CCU GHG accounting guideline

The focus was on GHG emissions arising from energy use and CO_2 flows across CCU processes, as well as those occurring up- and downstream of the CCU fabrication facility. GHG emissions embedded in bought-in materials across the value chain/life cycle were not included; the types

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[1] In the title, abstract or text (excluding medical research)
[2] Technical Summary, p. 48

of material employed are highly proprietary and were not made available to the authors. Similarly, emissions arising from CO_2 transport and CCU-derived product transport were excluded. Generally, the approach involved cradle-to-gate analysis, although for some products the emissions arising downstream from product use were included to address concerns relating to the ‘permanence’ of GHG emission reductions achievable by CCU technologies.

The purpose of this particular report from the assignment is to provide a synthesized overview of the entire study findings. It is set out as follows:

> **Section 2** – provides a brief synopsis of current political activities to support CCU, including the state-of-play with regards to GHG emissions accounting and measurement, reporting and verification (MRV) approaches relevant to CCU.
>
> **Section 3** – presents a brief summary of CCU activities around the world, based on a database of projects compiled during project implementation;
>
> **Section 4** – sets out a summary of the CCU case studies analysed, although the full scope of data and information collected is not presented due to overriding confidentiality concerns of operators;
>
> **Section 5** – provides a summary of the results of composite life cycle GHG inventory compilation;
>
> **Section 6** – summarises the main conclusions drawn from the research undertaken.

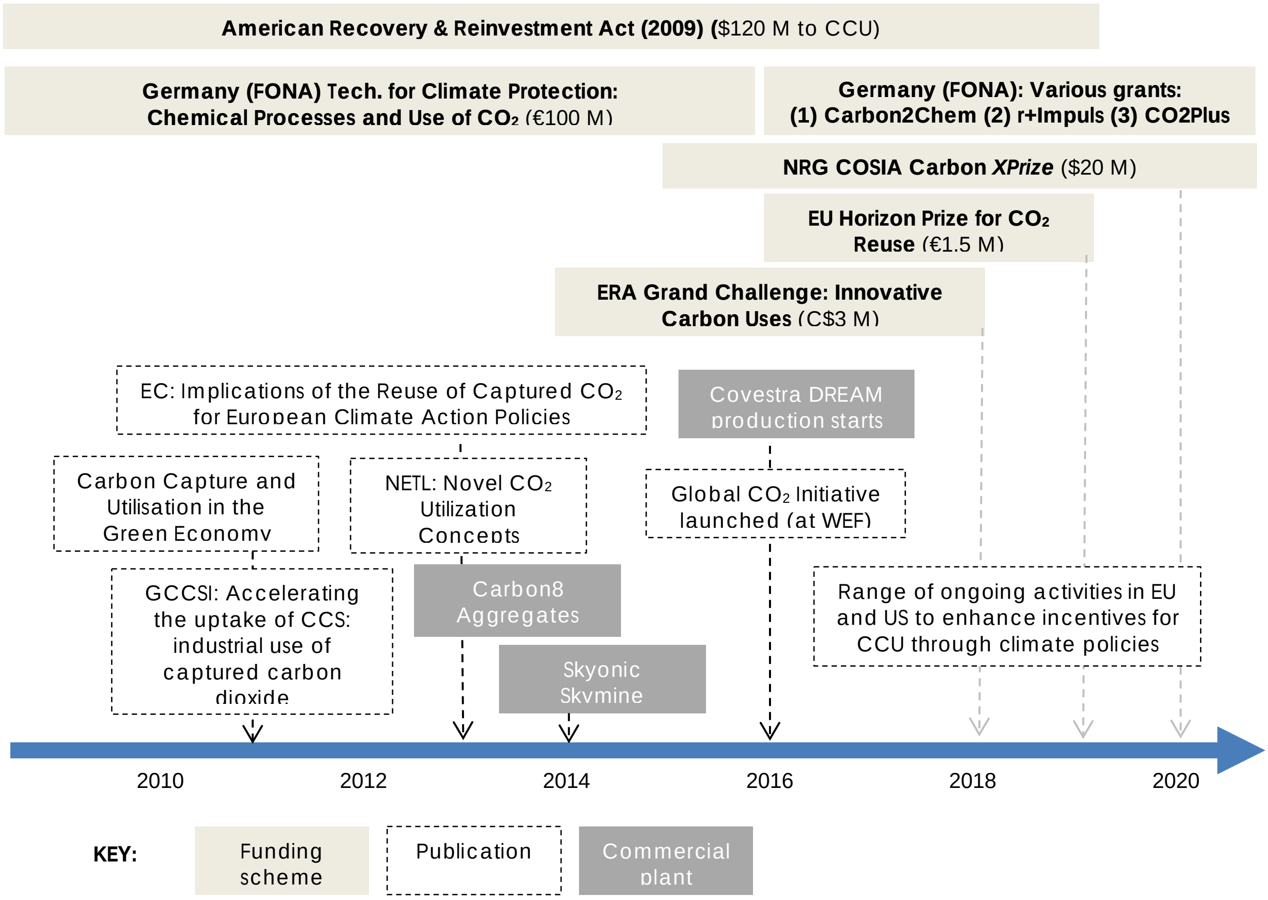
A separate document setting out an initial GHG emissions accounting guideline for CCU technologies is also presented alongside this synthesis report.

2 POLICY DEVELOPMENTS IN SUPPORT OF CCU

2.1 The Growing Interest

As highlighted above, interest in CCU technologies has grown extensively over the past 10 years or so, with some of the key milestones summarised schematically below (Figure 2.1). Activities include 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 programmes collectively exceeded US$200 million in grant support for at least 50 CCU activities. Other smaller-scale support has also been offered by the European Commission and the Governments of the United Kingdom (UK) and France.

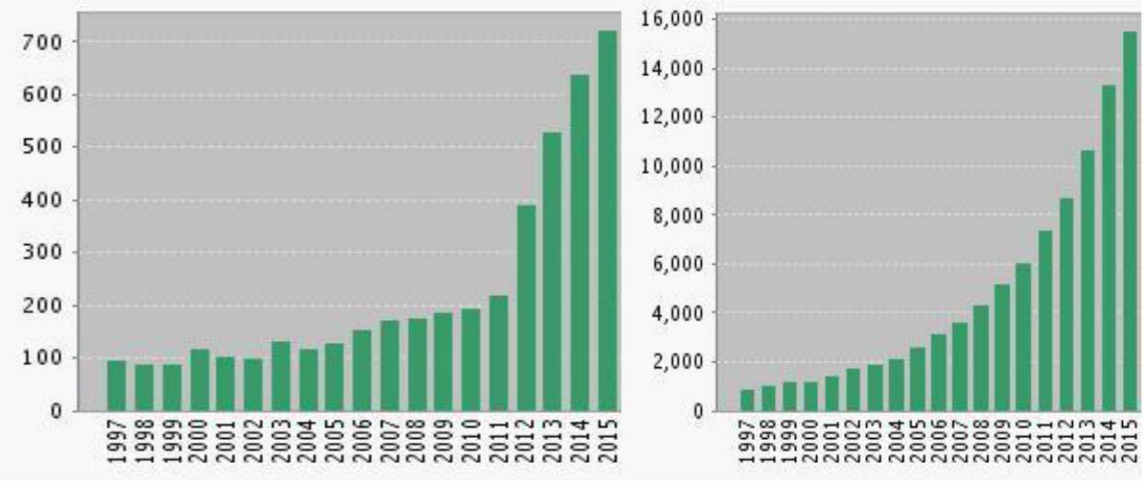
Figure 2.1 Recent and ongoing milestones for CCU development (2009-2020)



The increase in scientific and research interest is also notable, demonstrated by the increasing number of citations in scientific journals as described previously. The level of citations over time since the late 1990s to 2015 is shown below (Figure 2.2).

Taken together, the growth in research funding, pilot plant launches and journal citations can be taken as evidence of the growth in interest in the technology over recent years.

Figure 2.2 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*)

2.2 Drivers for Development

To an extent, the growing interest in CCU 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. 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 form 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 European Union, where the European 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, 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 latter 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.[7] Similarly, although the EU considers the topic of CCU under the scope of the European Commission’s

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[7] 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.’

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, 2016), 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.

These efforts notwithstanding, uncertainty remains regarding the true potential of CCU technologies to deliver real, measurable, verifiable and scalable GHG emission reductions. This is in part 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.

Such a 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.

2.3 Policy Developments

Notwithstanding the ongoing asymmetry of information and its potential resolution in the next few years through e.g. 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 of boundary setting, emissions leakage and permanence in the accounting/MRV rules.

For example, proposals were made by the European Parliament early in 2017 to include CCU within the EU's GHG emission trading scheme (ETS) for Phase IV onwards (from 2021 onwards) despite its explicit exclusion under Regulation No. 601/2012 on monitoring and reporting under the EU ETS (the "MRR"; European Commission, 2012). This has now been conceded by the

European Parliament, however, and CCU will not be explicitly included at least until 2030[8]. CCU technologies will be eligible under the EU ETS Innovation Fund ('NER400+), where the technology:

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

Activities are similarly ongoing to recognise CCU-derived fuels within the Renewable Energy Directive's (RED) supplier obligation for low carbon transport fuels as and when it is revised over 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" [Furthering carbon capture, Utilization, Technology, Underground storage, and Reduced Emissions Act]. The FUTURE Act – originally put forward in July 2016 as the Carbon Capture Utilization and Storage Act – is receiving bi-partisan support from 24 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 supported 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 group is also backed by leading internationally-recognised 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). 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).

In all cases, regulators have provided clear signals that inclusion of CCU technologies into climate change mitigation policies and incentives is subject to resolving the GHG accounting and MRV uncertainties and challenges outlined below.

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[8] Although it can still be "opted-in" before 2030 by Member States proposing amendment of the MRR.

2.4 Challenges to Inclusion in Low Carbon Policies

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.

The basis for these discussions is unclear, however, 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. A second factor is scale. Most studies conclude that the mitigation potential of CCU 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. 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 that can be employed to account for GHG emissions and emission reduction benefits from CCU.

2.4.1 Efficacy of Mitigation

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 (see Section 5 below).

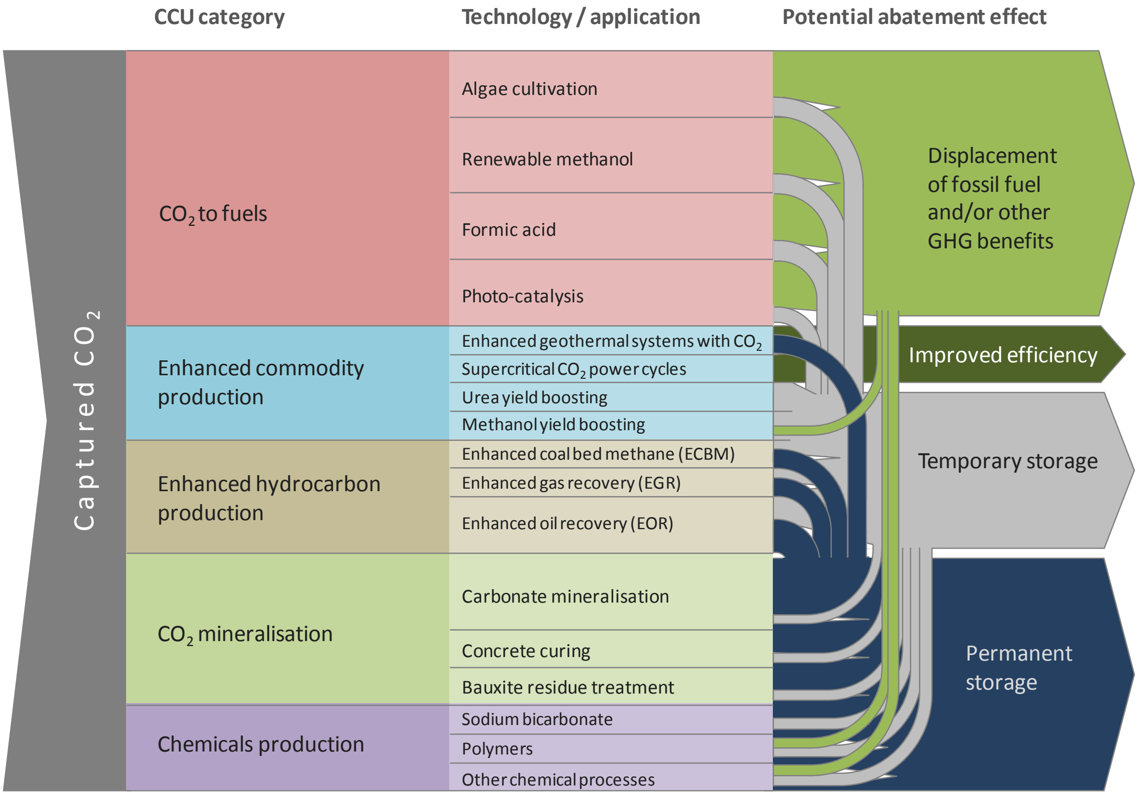
Another challenge is the source and quality of CO_2 that can be used in CCU applications. Most applications to date have involved the use of a fairly pure stream of CO_2, meaning that capture and purification of combustion exhaust gases will generally be required before use. As such, further energy and materials consumption is involved upstream of the CCU process. Research has been fairly limited regarding 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; in some cases this CO_2 may be manufactured from burning natural gas.

Furthermore, many of the GHG emission reduction benefits of CCU are predicated on the 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, and the capture and supply of CO_2 from flue gases reduces point source emissions. 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 2.3), 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.

Figure 2.3 Illustrative emission reduction pathways for CCU technologies



Source: European Commission, 2013

Such concerns over the efficacy of CCU technologies as a GHG mitigation approach are not new. 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 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.

2.4.2 Scale of Mitigation Potential

The uncertainty regarding the type and pathways for GHG emission reductions created by CCU technologies means 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. 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.[9] The numbers provided were for estimated CO_2 *demand*, rather than CO_2 *abatement potential*. Alternatively, at around the same time, Det Norske Veritas (DNV, 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, 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 2.1).

Table 2.1 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

2.5 Designing GHG Accounting Methods

In addition to the uncertainties described, a further issue to be addressed today relates to the question: what is the purpose to be served by an emission accounting framework for CCU technologies? In essence, discussions in these contexts relate to 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

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

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 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 low emission products to 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 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 pricing 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), 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 2.1).

Box 2.1 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 GHG emission reduction 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.

The results of this research programme – as summarised in subsequent sections of this report – therefore provide a timely addition to the knowledge base and a useful intervention in the ongoing political debates taking place around CCU. The methods and results can assist 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.

NOTE: The review presented in Section 2 is a summary of a more detailed assessment contained in the forthcoming in the IEA GHG report: "Greenhouse Gas Emissions Accounting for Carbon Dioxide Capture and Utilisation (CCU) Technologies: Characterising CCU technologies, policy support, regulation and emissions accounting".

3 CCU ACTIVITIES AROUND THE WORLD

This section provides 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, the 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 complete online 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). 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 as a result of its funding source. Caution should therefore be exercised 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. In general it is difficult to track the precise progress of CCU activities, as many start-ups receive limited funding, achieve press coverage and operate for a number of years, but then dissolve, for example, as characteristic of a number of supported activities under the American Recovery and Reinvestment Act (ARRA) funding.

In undertaking this assignment, a database of current CCU activities around the world was compiled, building from the aforementioned studies, and application of further effort to address the shortcomings of these databases. This analysis suggests that around 200 CCU projects are currently, or have recently been, in operation worldwide. Of these, 113 projects are considered to be still active today. These range in scale from small-scale demonstration projects to commercial operations.

Compiling the estimates outlined has provided insights 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, the compiled database exhibits the following characteristics regarding global CCU activity:

- Of the 200 projects in the database, 113 (57%) are believed to be ongoing
- Approximately 9 out of 10 CCU projects (90%) are located in North America or Europe, with the largest proportion in the EU. The country with the largest number of projects is the US (66), double the next country, Germany (Figure 3.1);
- Analysed by type, 43% of projects aim to produce fuels, with just over one-third intended to produce chemicals and one-fifth applying mineralisation (Figure 3.2).

- Looking more closely at specific CCU technologies, the most prominent are catalytic conversion, algae and carbonates (Figure 3.2), together accounting for 59% of all projects
- The distribution of projects by scale demonstrates a logical pattern, with the largest category being bench/R&D scale, decreasing in steps to the smallest category, commercial scale (Table 3.1)
- Closer analysis reveals that a greater proportion of mineralisation projects have reached commercial status than have fuels or chemicals projects (Table 3.1); fewer than half of chemicals projects go beyond bench/R&D scale; and fuels projects are the least likely to be commercial

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.

Figure 3.1 Global geographical distribution of CCU projects

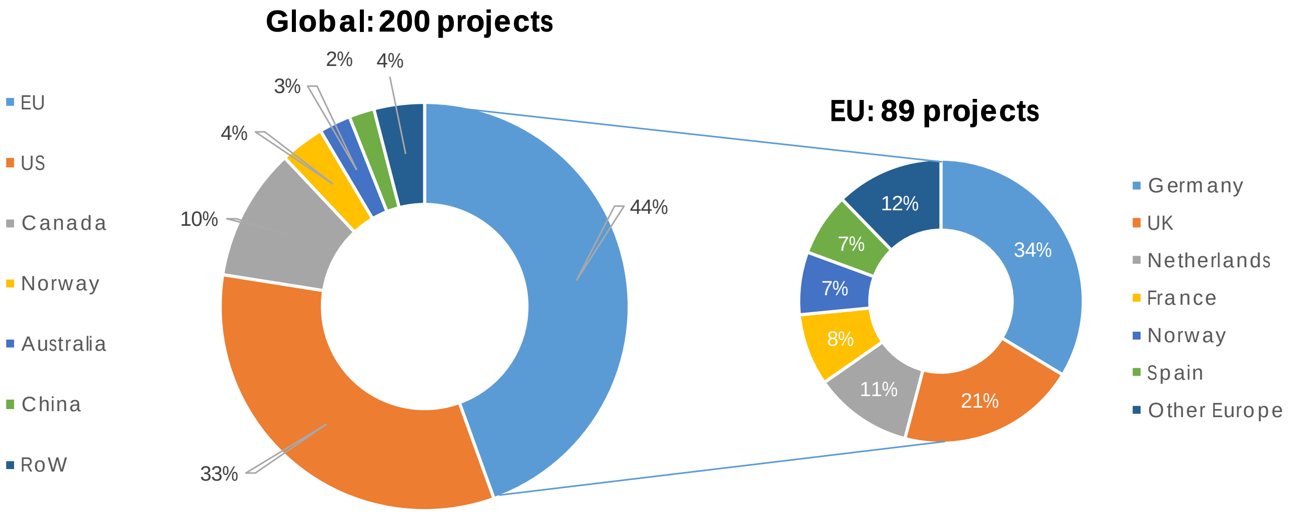


Figure 3.2 Distribution of global CCU projects by type and sub-type

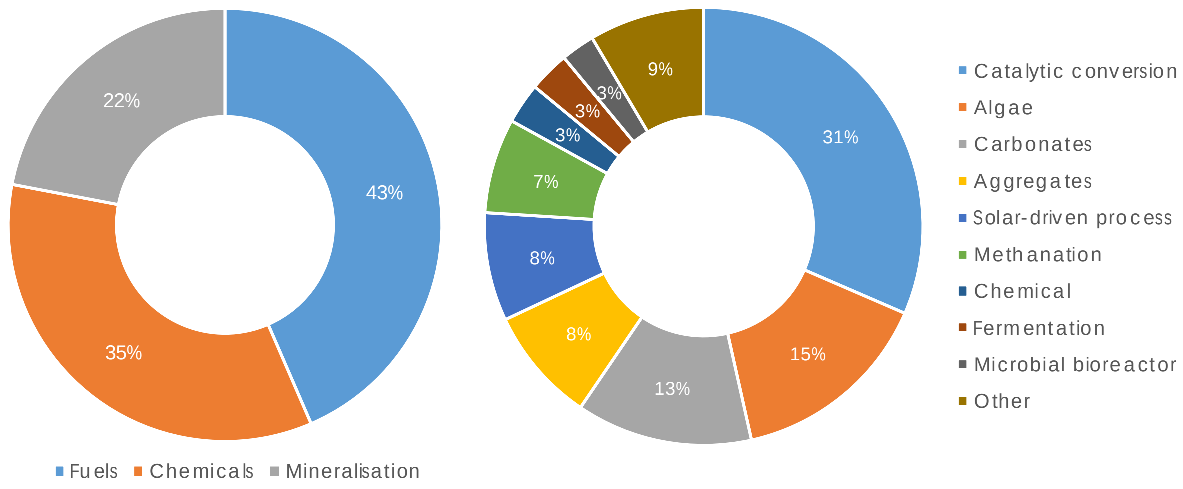


Table 3.1 Global CCU projects by type and scale

		TYPE			
		Fuels	Chemicals	Mineralisation	**Total**
SCALE	Bench/R&D	37	38	12	**87**
	Pilot	23	15	19	**57**
	Demo	22	10	3	**35**
	Commercial	5	6	10	**21**
	Total	**87**	**69**	**44**	**200**

3.2 Funding for CCU, Including Prizes

In terms of funding, the CCU database shows the following:

- Provision of government funding for CCU projects approximately reflects the geographical distribution of project activity
- Data show that the EU, US and Germany award higher individual grants than others
- The largest single award was for US$36 million under ARRA (American Recovery and Reinvestment Act), to a project that has now ended
- 24% of projects have been awarded a Prize/Grand Challenge (financial or non-financial)
- 22% apparently received no award (financial or non-financial) or grant
- While it appears that most projects were not government funded, the data are considered incomplete

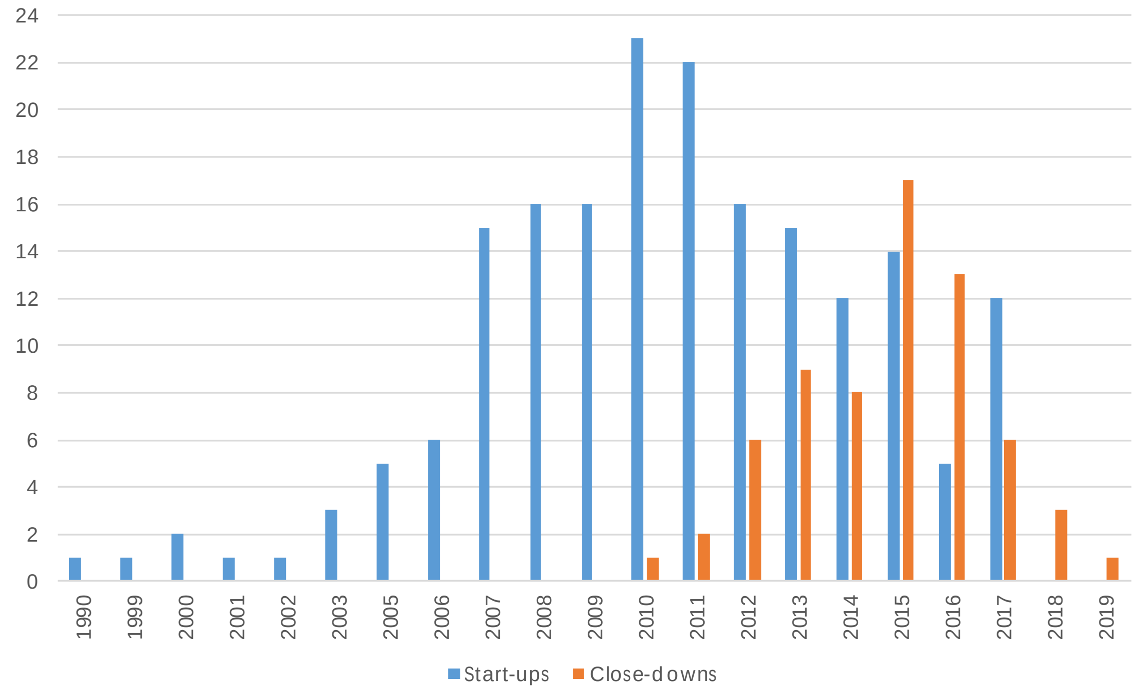
3.3 Changes over Time

The CCU database shows the following characteristics for CCU development over time:

- The data show a clear pattern of CCU project activity over time, with project start-ups peaking in 2010 (possibly in response to increasing government spending after the global financial crisis) and close-downs peaking in 2015 (coinciding with the collapse in global oil prices)
- Data for 2017 indicate an increase in start-ups compared to 2016, but it is too early to identify this as a trend

The general trend in start-ups and close downs is shown graphically below (Figure 3.3).

Figure 3.3 CCU Start-up and Close-downs per year (from 1990)



4 FACILITY LEVEL GHG EMISSIONS ASSESSMENT

4.1 Overview

Detailed analysis of several CCU case studies covering specific facilities was undertaken in order to draw out real-world experiences in CCU process operation. The data and information collected was used as a basis for subsequent development of composite GHG emission profiles for CCU activities incorporating up- and down-stream emissions and the determination of CCU GHG performance (Section 5), and for proposing GHG accounting rules specific for CCU technologies as set out in the accompanying report: *Greenhouse Gas Accounting Guidelines for CCU v1.0*.

A number of CCU operators were approached to assess their potential involvement. These included key CCU projects and technology developers worldwide covering a broad range of CCU technologies and pathways. The following operators/projects agreed to participate as case studies:

- *Carbon8 Aggregates (UK)* – carbonate mineralisation from CO_2 and industrial waste residues to produce aggregates
- *Carbon Recycling International, CRI (Iceland)* – methanol production from CO_2 and hydrogen produced from water electrolysis; ‘renewable methanol’
- *Algenol Biofuels (US)* – ethanol production from cyanobacteria algal production utilising CO_2
- *Weyburn-Midale EOR project (Canada/US)* – enhanced oil recovery (EOR) utilising CO_2 from coal-fired power generation and coal gasification plants

Discussions and site visits were used through 2017 to collect and verify site-level data and information covering the following areas:

1. Description of CCU production process and products(s)
2. Description of facility lay-out, production units, utilities, etc.
3. Energy consumption (energy sources, fuels used etc.)
4. Carbon flows (sources of utilised CO_2, emissions sources, CO_2 in product etc.)
5. Material usage and production (catalysts, water, waste material inputs and outputs etc.)
6. Operational and performance information (constraints, process optimisation aims etc.)
7. Measurement and monitoring (techniques, metering etc.)
8. Market, policy and regulatory factors

The scope of the GHG assessments undertaken for each of the CCU case studies is summarised in the table below (Table 4.1), showing which emissions sources were covered by the site-level assessments and which sources were instead compiled from the literature in relation to up- and down-stream emissions (see next Section).

Table 4.1 Scope of analysis for detailed GHG assessments

Scope	Activity	Covered/ Not Covered	Note on choice
Scope 1	**CO_2 capture / generation** (feedstock; energy use; fugitive emissions)	✔	Excluded from site assessments for the following main reasons: 1. Many sites employing CCU today are not using captured anthropogenic CO_2, but rather use other sources such as bought-in CO_2. 2. The energy and CO_2 balance for the capture process can be highly variable, which will skew results according to the efficacy of the CO_2 capture technique employed (or any assumptions made to model capture). In our opinion, considering this element will detract from the more important analysis required for the actual core CCU process.
	CO_2 input (amounts fed into process)	✓	Required to prepare a CO_2 balance for the CCU process in terms of the amount of CO_2 feedstock needed/input, the uptake rate into product, any emissions resulting from inefficient capture, and the amount that leaves a site integrated into the final product.
	Direct process CO_2 emissions (venting/fugitive emissions)	✓	
	CO_2 in product (utilised and exported from site)	✓	
	On-site heat and power generation (stack emissions)	✓	Needed to compile the full CO_2 balance for the process in terms of energy related emissions
	Road transport (staff travel/commuting, logistics)	✗	Excluded as highly site specific
Scope 2	**GHG emissions from bought-in heat and power** (grid emissions factor; emissions from purchased heat)	✓ ✔	Needed to compile the full CO_2 balance for the process in terms of energy related emissions. Sensitivities will be assessed to account for different circumstances/grid emission factors.
Scope 3	**GHG emissions embedded in bought-in goods/services** (feedstocks etc.)	✗	Excluded as highly process specific. Also, it is unlikely that we will obtain a full inventory of materials used. It would also require LCA databases to calculate the GHG footprint of the individual materials used
	GHG emissions from fuel use in capture / generation (extraction, processing, biomass harvesting etc.)	✔	Needed to assess the additional fuel use and associated GHG emissions (associated with the CO_2 capture energy penalty) arising upstream of the capture source
	GHG emissions due to product substitution "downstream effects"	✔	Excluded from site assessments, but to be assessed from literature. The substitution effect of displacing more GHG intensive incumbents is likely to be a key climate change benefit of CCU derived products.

Key: ✓ = Compiled from site assessments; ✔ = Estimated from literature; ✗ = Excluded from study

This section presents a summary of the case studies. The focus is upon the facility-level technology and processes deployed; for reasons of confidentiality, detailed energy, materials consumption and emissions data used to compile the composite GHG emission profiles and GHG performance assessments are not presented.

4.2 Carbon Recycling International (CRI): Renewable Methanol

4.2.1 Overview

Carbon Recycling International (CRI) operates a CO_2-to-methanol production process via direct hydrogenation of CO_2 feedstock, termed by the company as the "CRI ETL" (emissions-to-liquids) system. The process can be applied in a number of different configurations, depending upon the availability of hydrogen feedstock, the renewable electricity source, and the characteristics of emissions used to source the CO_2 feedstock (CRI, 2017a). The CO_2 feedstock can be sourced from a variety of upstream processes, ranging from high purity sources, such as geothermal power plants or ethanol plants, to post-combustion and more diluted sources such as steel mills and chemical plants. The hydrogen feedstock can either come in a highly pure form split from water or through sodium-chloride electrolysis, as well as from a waste gas streams involving H_2 separation (e.g. coke oven gas; *ibid*).

The resulting 'renewable methanol' product – branded as Vulcanol^{TM} – can be used as a 'drop-in' substitute in various applications, with the company's focus being on transport fuel substitution. Methanol is currently used in several European Union (EU) member state countries as a blend component in gasoline meeting EN 228 fuel specifications where up to 3% volume blending is permitted. Direct use of methanol in marine engines has been demonstrated in Sweden, and electric vehicles using methanol fuel cells are in operation in Denmark. The recognition of the GHG intensity of renewable methanol production as operated by CRI under the EU Fuel Quality Directive (FQD) would expand the market potential for renewable methanol further within Europe; consideration of CCU-derived fuels within the FQD is currently in progress. Methanol can also be used as a chemical feedstock for many common building blocks for basic materials.

CRI has already demonstrated the ETL system at industrial scale at the CRI George Olah Plant located at Svartsengi, near Grindavik in Iceland (Figure 4.1). The plant produces methanol from CO_2 provided by the adjacent geothermal power plant and hydrogen derived from water electrolysis using electricity from the Icelandic grid, which is supplied by hydro and geothermal sources. In practice, although it has a grid supply, the electricity is delivered more or less direct from the neighbouring geothermal plant, and is interruptible if the grid system operator needs to increase the amount of grid-dispatchable power from Svartsengi. The plant was first commissioned in 2012, with sufficient hydrogen capacity to produce 1,300 t/year methanol and one alkaline water electrolyser rated at 2 MWe. Expansion in 2015 and the addition of two 2MWe electrolysers increased the facility's name-plate capacity to 4,000 t/year (*ibid*).

Since February 2013 the plant's GHG intensity performance has been certified under the *International Sustainability & Carbon Certification* (ISCC) PLUS scheme and independently audited by SGS Germany.[1] The low GHG intensity of the product produced at the existing facility is based on the renewable energy source and capture and utilization of CO_2 emissions which would otherwise be released to atmosphere.

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[1] The International Sustainability & Carbon Certification (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). 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).

Through 2018 and 2019 CRI plans to deploy new ETL systems under two separate EU Horizon 2020[1] research and innovation program grants, entitled MefCO_2 and FReSMe. CRI's contribution to these consortium projects will be based on the direct CO_2-to-methanol synthesis technology developed at the George Olah Plant, but with smaller production capacity and variations to the process and reactor design. CRI has also been working on pre-feasibility studies to assess the technical and economic feasibility of a number of commercial-scale ETL facilities in collaboration with several partners worldwide, based on different CO_2 and H_2 sources (*ibid*).

Figure 4.1 CRI George Olah Renewable Methanol Plant, Svartsengi, Iceland

Source: Authors

4.2.2 Description of CCU Process

Figure 4.2 shows a simplified flow diagram of CRI's ETL CO_2-to-methanol production technology, showing the main sources of potential GHG emissions from electricity and steam consumption as well as raw materials. Each of the five key process elements shown in the figure are described further below, based on information provided by CRI (CRI, 2017a).

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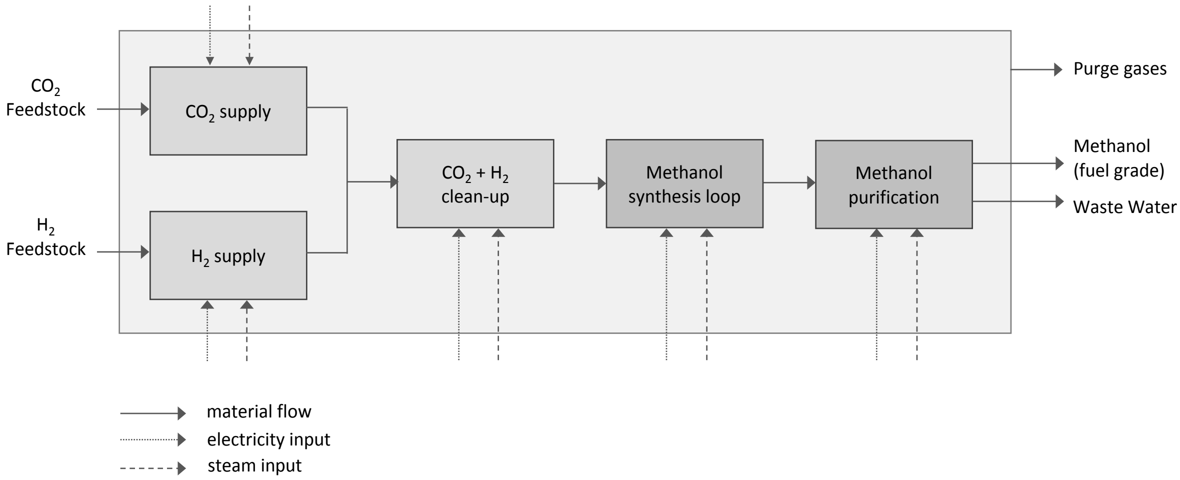
[1] Horizon 2020 is the EU's research and innovation funding programme for the period 2014-2020

Figure 4.2 Simplified flow diagram of CRI renewable methanol production



CO_2 Supply Unit

The CO_2 feedstock for renewable methanol production can be sourced from a variety of upstream processes covering a range of CO_2 concentrations. In the CO_2 Supply Unit, the CO_2 feedstock stream is concentrated to the required concentration for use in the downstream production units (>99% mol. for the George Olah plant). High concentration CO_2 streams such as those from the production of fertilizer, ethylene oxide, ethanol and biogas upgrading require only minimal processing before use. Less concentrated emission point sources such as thermal power plants, steel, cement and refineries require the use of carbon capture equipment, in which case energy consumption and consumables need to be accounted for in the GHG balance.

H_2 Supply Unit

The required H_2 feedstock can be generated through electrolysis, through steam methane reforming (SMR) of natural gas, or recovered from a suitable industrial waste gas stream (e.g. by applying pressure swing adsorption (PSA) to coke oven gas (COG)). It can also be supplied from a high concentration waste H_2 stream, in which case no unit is required: if waste H_2 is readily available at a concentration above 97% mol. H_2, no treatment is required to generate or concentrate the stream. The H_2 feedstock at the George Olah Plant is provided through electrolysis of water supplied from the adjacent geothermal plant (which sources water from boreholes). In the electrolysis cells, a current is applied between a pair of inert electrodes immersed in the electrolytic solution. The current dissociates the water molecules into hydroxide [OH^-] and hydrogen [H^+] ions. The positively charged H^+ ions move towards the cathode while the negatively charged OH^- ions move towards the anode. At the electrodes, electrons are absorbed or released by the ions forming H_2 and O_2 gas at the cathode and anode, respectively.

CO_2 and H_2 Clean-up Unit

The high concentration CO_2 and H_2 streams from the CO_2 Supply Unit and H_2 Supply Unit, respectively, are directed to the CO_2 and H_2 Clean-up Unit to remove trace compounds present in the feedstock streams which act as methanol catalyst inhibitors, particularly sulphur and chlorine compounds. Concentrations of sulphur and chlorine compounds need to be reduced to the parts per billion (ppb) level before the stream enters the methanol reactor (see below).

Depending on the composition of the input H_2 and CO_2 streams, three different options can be considered for the CO_2 and H_2 Clean-up Unit:

1. *CO_2 Stream Guard Vessel*: applicable when only trace (ppm) levels of sulphur and chlorine compounds are present and only in the CO_2 stream. In this case, the H_2 stream is sent directly to the Methanol Synthesis Loop (see below) while the CO_2 stream first passes through a pre-heater and guard vessel to remove trace sulphur and chlorine compounds.
2. *CO_2 + H_2 Stream Guard Vessel*: applicable when only trace (ppm) levels of sulphur chlorine compounds are present in both the CO_2 and H_2 streams. In this case, the combined CO_2 and H_2 stream passes through a pre-heater and guard vessel to remove trace sulphur and chlorine compounds.
3. *Methyldiethanolamine (MDEA) H_2S capture from CO_2 stream + CO_2 Stream Guard Vessel ("CO_2 capture")*: applicable when the H_2S concentration in the CO_2 stream is relatively high (above ppm level).

The George Olah Plant adopts option (3). In the MDEA absorption system, the CO_2 stream enters the bottom of the absorber column while the liquid MDEA solvent enters the top of the column. The counter-current flow, along with the internal trays or packings inside the column to improve mass transfer effects, results in transfer of H_2S and some CO_2 from the gas stream to the liquid stream through absorption (due to the liquid solvent's H_2S affinity). The rich solvent leaving the bottom of the absorber column is then directed to the stripper column for regeneration through heating. Raising solvent temperature reduces H_2S and CO_2 solubility, resulting in the release of H_2S and CO_2 from the solvent to regenerate a lean-MDEA stream to be directed back to the absorber column for re-use.

The MDEA system can only reduce H_2S concentration down to the ppm level and further treatment in a guard vessel is required to remove trace sulphur and chlorine compounds. Depending on the specific contaminants present, the guard vessel may require operation at temperatures of up to 200^{o}C to remove certain compounds requiring the use of an electric pre-heater. This configuration assumes that no trace sulphur and chlorine compounds are present in the H_2 stream, and the H_2 stream is sent directly to the Methanol Synthesis Loop (see below).

Methanol Synthesis Loop

The make-up CO_2 and H_2 stream from the Clean-up Unit is pressurised to reaction pressure and mixed with the loop circulation flow. The combined stream is passed through an interchanger for pre-heating before being sent to a reactor where it is partially converted to methanol and water through the following primary reaction:

$CO_2 + 3\ H_2 \rightarrow CH_3OH + H_2O$

The partially converted syngas is then cooled and sent to a gas-liquid separator. The liquid from the separator consists of crude methanol, mainly a combination of methanol and water, which is then sent to the Methanol Purification Unit to extract the methanol product (see below). Part of the unreacted gas stream from the separator is purged to prevent build-up of inert gases (mainly N_2) in the Synthesis Loop, which reduces process conversion in the reactor. The remainder of the unreacted gas stream forms the loop circulation flow which is sent to the circulator for recompression before mixing with the fresh make-up CO_2 and H_2 stream from the Clean-up Unit. The recycling of unreacted gases in the Methanol Synthesis Loop improves the overall process conversion.

Various heat recovery configurations in the Methanol Synthesis Loop have been designed to reduce the steam utility consumption in the Methanol Purification Unit (see below). These include the addition of a Loop Steam Boiler in the Methanol Synthesis Unit to supply steam for use in the distillation column reboilers, and the addition of a heat exchanger upstream of the Methanol Condenser to pre-heat the distillation column feed.

Methanol Purification Unit
A distillation system is used to separate methanol from heavier components in the crude methanol. The system consists of one or more distillation towers, reboilers, condensers and separators. A reboiler is connected to the bottom of the tower, evaporating a part of the liquid to send it back into the tower. A condenser is connected to the top of the tower, condensing overhead column vapours to form the methanol product and/or liquid stream to be sent back into the tower. The water stream from the distillation system is cooled and pumped away for waste water treatment. For fuel grade methanol, one column is sufficient – as applied at the George Olah plant – but two columns are required for chemical grade methanol. The complexity of the methanol purification step has impacts for the plant’s overall steam consumption.

The water from the bottom of the distillation system contain traces (ppm level) of methanol and other higher alcohols. The alcohols in the water bottoms are biodegradable and treated as such according to local conditions and regulations.

Process and Performance Optimisation
As described above, several factors determine the facility-level energy efficiency of the production process. The most important of these is whether H_2 is available in pure form i.e. as a high concentration waste gas stream, or whether it must be produced or concentrated from a suitable industrial gas stream. The composition of the CO_2 and H_2 streams also determine the degree of clean-up required and therefore the overall plant efficiency. In addition, various heat management options exist at the methanol synthesis and purification stage. The characteristics and availability of CO_2 and H_2 feeds are thus a key determinant of process performance.

CRI indicates that electricity consumption per unit methanol produced at the George Olah Plant is higher than would be expected for future, larger plants due to process optimisation and the higher relative contribution of non-process-related equipment such as auxiliary systems, lighting and operator control facilities. In addition, the company claims that feedstock conversion rates would be improved for larger commercial scale plant designs, according to various plant optimisation factors (CRI, 2017a).

4.3 Carbon8 Aggregates: Carbonate Mineralisation

4.3.1 Overview

Carbon8 Aggregates Ltd (C8A) uses a patented carbonate mineralisation process, termed by the company as “Accelerated Carbonation Technology” (ACT), to manufacture a high quality lightweight aggregate marketed as C8Agg (C8A, 2017a). The ACT process uses pure CO_2 as a feedstock to treat industrial thermal residues. The CO_2 chemically binds with the free lime component of the thermal residues to form calcium carbonate, thereby permanently storing CO_2 which (depending upon its source) would otherwise be emitted to the atmosphere. C8A's process, for which it holds worldwide patents, has been developed following 15 years of research undertaken at Imperial College London and The University of Greenwich (C8A, 2017a).

The aggregate product is supplied to the building block manufacturing industry as a constituent of concrete construction blocks for use in the construction industry (C8A, 2017b). As well as capturing and storing anthropogenic sources of CO_2 therefore, the process also has the potential (depending upon its facility-level emissions performance) to substitute equivalent products manufactured with higher levels of GHG intensity. At present however, the main commercial driver for the company's operations is provided by the EU and UK's waste regulatory framework; specifically the ability under waste hierarchy legislation for EfW operators to send their thermal residues for treatment by C8A, thereby avoiding significant 'gate fees' (charges) imposed by landfill taxes.

The company currently operates three production facilities, located in the UK:

- *Brandon, UK*: Following various scaled trials, the first commercial facility was built in early 2012 at Brandon, Suffolk, beside *Lignacite Ltd*'s masonry plant. A partnership between C8A and *Lignacite* resulted in the development of the "*Carbon Buster"* building block. The facility receives thermal residues from several EfW facilities including the Lakeside facility to process into aggregate. In 2014, the company built a second production line, doubling its treatment capacity to produce over 50,000 tonnes of aggregate per year (C8A, 2017a)
- *Avonmouth, UK*: A second facility was constructed at Avonmouth, near Bristol, in 2016. The plant produces up to 100,000 tonnes of aggregate per year and includes a larger silo storage system for incoming residues, storage for associated fillers and binders, a new building to house the processing equipment, and covered storage bays for aggregate product. The facility receives thermal residues from a number of energy from waste plants across the south of the UK
- *Leeds, UK*: A third facility at Cross Green was completed in 2018. The new site has been developed alongside a new block production plant operated by local independent block-making company, *Thomas Armstrong* (C8A, 2017c). The plant has been fitted with more advanced systems for handling incoming waste, fillers and binders. The facility will receive thermal residues from several sites in the north of England.

As of the time of writing, Carbon8 Aggregates are planning the construction of their fourth site. C8A currently have plans to develop further sites around the UK with a combined production capacity of 250,000 tonnes of waste per annum (C8A, 2017c).

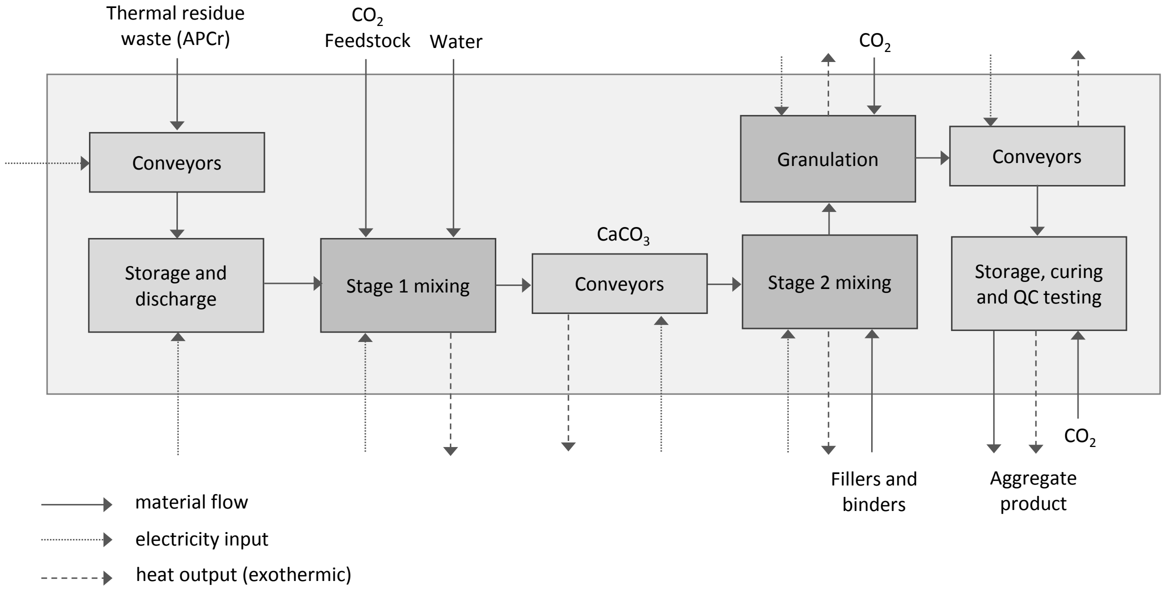
Figure 4.3 Carbon8 Aggregates facility at Avonmouth, UK

Source: Carbon8 Aggregates

4.3.2 Description of CCU Process

Figure 4.4 shows a simplified flow diagram of the production process, based on the company's two-line production facility at Avonmouth.

Figure 4.4 Simplified flow diagram of Carbon8 aggregate production



The core facility consists of a three-stage treatment process. The general mode of operation is similar to that of a concrete batching plant. Thermal residues (air pollution control residues, flue gas treatment wastes, fly ashes, boiler dusts, bottom ashes), arrive in powder tankers and are pneumatically conveyed into one of several storage silos. The silo storage and discharge system is designed so that the contents of each silo can be blended in the required proportions to achieve consistency. The blended untreated waste is then screw conveyed to a vessel (Figure 4.5) where water and liquid CO_2 are added to convert the free lime into calcium carbonate, and to chemically stabilise any contaminants. The CO_2 is delivered by tanker on a commercial basis with an industrial gas supplier (C8A, 2017b).[1]

Adding water to the free lime (calcium oxide, CaO) produces hydrated lime (calcium hydroxide, $Ca\ (OH)_2$) in a strongly exothermic reaction according to:

$$CaO + H_2O \rightarrow Ca\ (OH)_2$$

The resulting calcium hydroxide reacts with the CO_2 feedstock to produce calcium carbonate ($CaCO_3$) according to:

$$Ca\ (OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O$$

The resulting non-hazardous calcium carbonate powder is transferred by belt conveyor to a second vessel where fillers and binders are added as necessary. The material is then transferred to drum pelletizer units where the material is granulated. The resulting product is then transferred on delay conveyors to one of several storage bays for final curing, and sampling and quality control testing.

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[1] The CO_2 utilised is understood to represent anthropogenic (industrial) sources which would otherwise be emitted to the atmosphere: the CO_2 delivered to the Brandon facility is sourced from sugar beet processing; the CO_2 delivered to the Avonmouth facility is sourced from a fertiliser production plant (Carbon8, 2017b).

Figure 4.5 First stage vessel at the Carbon8 Brandon facility

Source: Carbon8 Aggregates

Process and Performance Optimisation

Carbon8 Aggregates have optimised the performance of their Avonmouth facility in terms of energy and materials efficiency, based on the scale-up from the Brandon plant and various process improvements. Further improvements have been made at Leeds. Improving the carbon footprint of the production process represents an ongoing objective. This includes assessing the role for low-carbon energy sources (e.g. solar), rainwater harvesting, heat recovery, using low-carbon fillers and binders, and potentially utilising CO_2 within flue gases (C8A, 2017b).[1] Because the main commercial driver for the process is currently the avoided cost of waste disposal, optimising throughput rates represent a major factor for process efficiency. These are limited by the maximum practical size of the mixing units, and by the rate of reaction between the thermal residue and CO_2.

4.4 Algenol Biotech: Algae-derived Ethanol

4.4.1 Overview

Algenol Biotech, LLC, (Algenol) is an industrial biotech company that develops bio-based products utilizing algae. The company was formed in 2006 and is headquartered in Fort Myers,

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[1] The CO_2 feedstock can potentially be provided to the process in lower concentrations than high-purity CO_2 (down to 70%), with no effect upon rates of reaction. Lower concentrations (such as those in flue gasses) can also be effectively used.

Florida, US, with an additional research and development facility in Berlin, Germany (Algenol, 2017). It has developed over 2,000 algal strains in order to meet a broad range of commercial application including the production of ethanol, proteins, enzymes, nutritional supplements and biochemicals. The Fort Myers facility undertakes research and development (R&D) activities as well as cultivation and commercial production. The site includes a number of laboratories dedicated to algae development and performance testing under various conditions. The facility's Process Development Unit (PDU) includes a 4.5-acre green-field facility designed specifically for large-scale outdoor R&D and cultivation using commercial scale photobioreactors (PBRs) (*ibid*). The company's production of algae-derived fuel products is branded as "Algenol Biofuels".

Figure 4.6 Algenol headquarters at Fort Myers, Florida, US

Source: Authors

In 2015, Algenol received US$ 25 million of funding from the US Department of Energy (DOE) to support the construction of a pilot Integrated Biorefinery (IBR) at the Fort Myers site to advance development of algal-based fuel production, producing fuel-grade ethanol from algae. Project partners include the National Renewable Energy Laboratory (NREL), Georgia Institute of Technology (GaTech), Membrane Technology and Research (MTR), and The Dow Chemical Company. Deployment began in January 2015 and was completed in May 2016. The project is currently in a revamping phase for operational optimization.

Algenol's Direct to Ethanol® technology is an integrated process for the production of liquid biofuels based on a proprietary strain of blue-green algae (cyanobacteria). The technology uses CO_2, salt water, sunshine and electricity to enable the growth of the algae in the PBRs. The algae actively carry out photosynthesis and utilize CO_2 as the feedstock for producing and secreting ethanol from each algal cell. Over 85% of the carbon input is converted into ethanol fuel, thereby allowing for the utilisation of CO_2 which might otherwise be emitted to the atmosphere. The company claims that for every gallon of ethanol fuel used, approximately two thirds of a gallon of fossil-fuel gasoline is displaced (Algenol, 2016). The utilisation of anthropogenic CO_2 and the displacement of fossil-based transportation fuels provide the potential for significant net GHG benefits on a life-cycle or "well-to-wheels" basis (Luo *et al.*, 2010; Lively *et al.*, 2015).

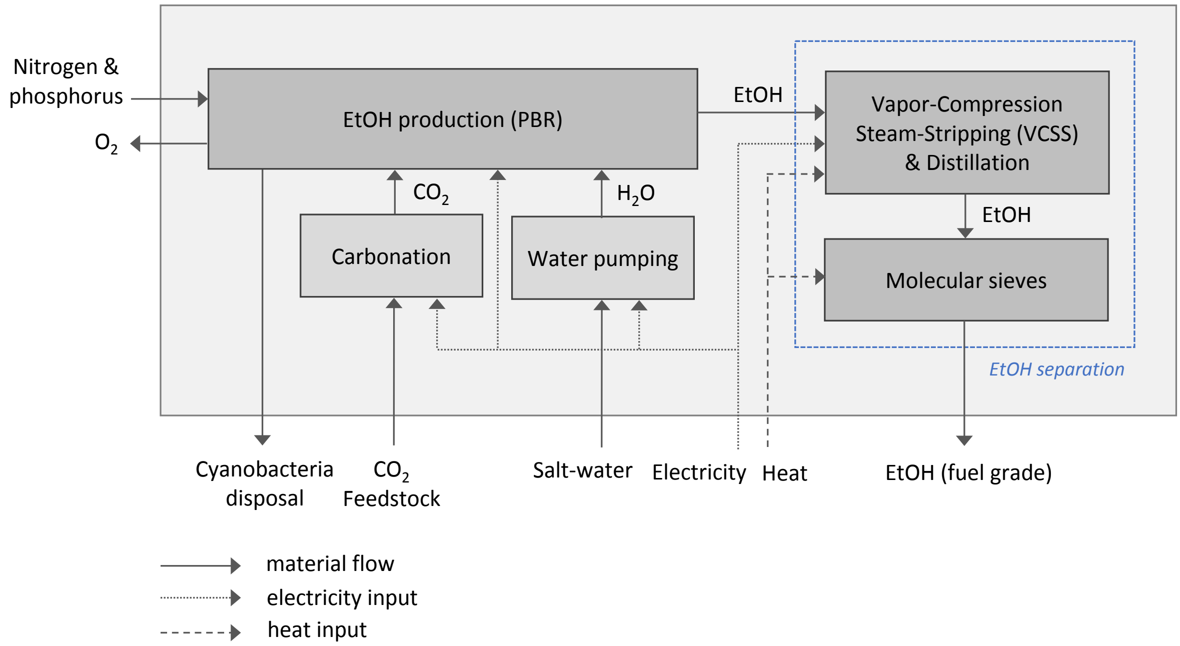
In addition to the GHG reduction benefits, Algenol claims that their Direct to Ethanol® technology does not require use of high-value land: the design of the PBRs that are hung from support systems means that low-cost, non-productive land can be utilised for growing the algae (*ibid*). Currently, CO_2 is sourced at the Fort Myers site from an industrial gas provider on a commercial basis. However, the land at future algae production facilities could be situated next to an industrial CO_2 source, allowing for the utilization of CO_2 that would otherwise be vented in the production of commercial scale ethanol fuel production.

4.4.2 Description of CCU Process

A simplified flow diagram of Algenol's Direct to Ethanol® technology is shown in Figure 4.7, summarising the key material and energy flows. The production process is described in Luo *et al.* (2010), Lively *et al.* (2015) and Algenol (2017). The ethanol-producing organisms are long-lived blue-green algae (genetically enhanced photoautotrophic cyanobacteria) grown in closed PBRs containing salt-water supplemented with CO_2 feedstock and small amounts of nitrogen and phosphorus fertilizers. The ethanol (EtOH) is collected from the PBRs as a dilute ethanol-freshwater solution from the cyanobacteria-seawater culture and purified to fuel grade ethanol. The cyanobacterial cultures are not harvested but are maintained for ongoing ethanol production.

The key processing step involves separating the ethanol from the seawater growth medium (Luo *et al.*, 2010). The ethanol separation process, which includes vapour compression steam stripping (VCSS), vapour compression distillation (VCD) and molecular sieving, is responsible for most of the process site-level energy use and GHG emissions. The main factor driving overall process efficiency and optimisation is the ethanol content in the liquid collected from the cyanobacteria. As described further below, the concentration of ethanol strongly affects the amount of energy needed to concentrate the ethanol: the higher the "initial" concentration of ethanol, the less energy is needed to purify the ethanol (*ibid*). Ethanol productivity in Florida ranges from 4,000-8,000 gal/acre-year dependent on season and process conditions; Algenol's target is to achieve over 7,000 gal ethanol/acre-year (Algenol, 2016).

Figure 4.7 Simplified flow diagram of Algenol algae-to-ethanol production



Source: Based on Luo et al., 2010 and Lively et al., 2015

Ethanol Production

The cyanobacteria are grown in flexible-film, polyethylene based photobioreactors containing salt-water as the culture medium (Figure 4.8). The proprietary PBRs are designed to be vertically hung from a lightweight support framework to maximise light utilization and oxygen and temperature management in outdoor cultures (Algenol, 2017).[1] The PBRs, arranged in a sequence of 'field- blocks' are exposed to sunlight and fed CO_2 and nutrients (nitrogen and phosphorous fertilisers). The production cultivation system has a header piping system that includes four main headers: air-in, air-out, liquid-in, and liquid-out. They are connected to the PBRs via tubing kits, with the liquid-in and liquid-out headers located below the PBR (*ibid*). The current pilot-scale production field is around 2 acres comprising around 6,500 10-ft wide PBRs.

The production of ethanol within the cyanobacteria-containing PBRs takes place according to the following basic reaction:

$$2\ CO_2 + 3\ H_2O \rightarrow C_2H_5OH + 3\ O_2$$

A mixing system for the PBRs is designed in much the same way as those for raceway ponds with three primary functions: uniform suspension of the cyanobacteria, uniform distribution of nutrients, and efficient transfer of gases (mainly CO_2) between the gas and liquid interface. Mixing within the photobioreactors is estimated to require 0.1 W/m^2 of energy. Assuming a 1% initial ethanol concentration, this corresponds to an energy requirement of 0.056 MJ/MJ EtOH (Luo *et al.*, 2010).

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[1] Vertical PBRs have a temperature mitigation advantage over horizontal PBRs likely due to indirect light exposure and larger surface area to volume ratio (Algenol, 2017).

Figure 4.8 Plastic film photobioreactors (PBRs)

Source: Authors

The raw salt-water used as the cultivation medium is sourced from a salt-water aquifer located below the Fort Myers facility. The well was drilled and commissioned in April 2013 at 1,600–1,800 ft depth (*ibid*). Luo *et al*. (2010) assume pumping of raw source salt-water to require 0.0066 MJ/MJ EtOH of electrical energy and pumping of the water-ethanol condensate into the separation system to require 0.004 MJ/MJ EtOH. Water sterilization, necessary for the initial fill of seawater and subsequent culture replacements, can be accomplished by ozonation with low energy requirements (*ibid*). Although it is possible to achieve at additional cost, the salt-water at the Fort Myers site is not currently recycled: the culture medium is instead made using new supplies of raw salt-water. 3 mol of water are needed to produce 1 mol of ethanol, i.e., 0.926 litre of water for each litre of ethanol (*ibid*).[1]

Options for delivering CO_2 feedstock include gas delivery to the headspace of the PBR, gas delivery to the culture, or CO_2-containing water delivered to the culture. At the Fort Myers site, pure CO_2 is currently delivered to the headspace from an industrial gas supplier on a commercial basis. Power plant flue gas CO_2 could also be used, although additional clean-up of flue gas may be required. CO_2 transfer from the headspace to the culture is aided by the mixing system, the higher delivery concentration compared to atmospheric levels, and the higher sorption of CO_2 in seawater compared to fresh water (*ibid*).

Ethanol production of 56,000 l/hectare-y corresponds to a nitrogen and phosphorus requirement of 0.065 g N/MJ EtOH and 0.0024 g P/MJ EtOH, respectively. Because of the no-harvest process, the cyanobacteria do not need to be continuously replenished, resulting in lower nutrient requirements than those for biofuel processes involving algal harvesting. Removal of the oxygen is accomplished through use of a compressor to extract the gas from the PBR headspace, and a gas scrubber for oxygen removal, with an energy requirement of 0.0001 MJ/MJ EtOH. The PBR production cycle runs for 3 to 6 weeks or longer: spent algae are then separated from the culture for chemical conversion or sequestration (Algenol, 2017). The resulting ethanol solution is transported to the ethanol separation facility (see below).

Ethanol Separation Process

The ethanol-freshwater solution first enters the vapour compression steam stripping (VCSS) unit, a highly heat integrated process that offers the potential for energy efficient separation even at low ethanol concentrations. Under normal process conditions, the feed flow rate to the VCSS is 4 gallons per minute (*ibid*). The unit concentrates the ethanol to a value in the 5-30% range dependent on the starting value and other details. Vapour compression distillation (VCD) is then applied to concentrate the ethanol to 94% (at or near the azeotrope[2]). A molecular sieve is then applied for the final stage to reach fuel-grade ethanol (99.7% concentration).

The ethanol separation process requires electricity and heat. For an initial 1% concentration, the energy consumption in converting the initial 1% stream to fuel grade ethanol is around 0.28 MJ/MJ EtOH assuming an 80% assumption for heat exchanger efficiency (Luo *et al.*, 2010). The sub-components of the separation process are described further below.

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[1] This replacement water can be provided by reverse osmosis seawater desalination, which requires about 8 kWhe per 1,000 gallon of water. This is 9.5 × 10-5 kWh/MJ EtOH.

[2] The azeotrope is a mixture of two liquids which has a constant boiling point and composition throughout distillation.

Vaporisation Processes

The concentration of ethanol produced by the steam-stripping column is determined by the input concentration of ethanol and the operating temperature of the column. For a 1% initial ethanol concentration, the steam-stripping column, operated at atmospheric pressure, will increase the ethanol concentration from 1% to 9.4%, and VCD operated at atmospheric pressure will raise the concentration of ethanol from 9.4% to 94%. The vapour from each steam-stripping column is condensed with a heat exchanger; the heat released from the condensation provides the heat for the steam-stripping column via a plate heat exchanger. The efficiency of the heat exchange process is an important variable in the assessment of overall energy efficiency of the VCSS system. For plate heat exchangers, 86% heat recovery is achievable in practical devices, with higher recoveries possible at higher capital cost (Kumar, 1983). A conservative assumption of an 80% efficient heat exchange is assumed as the baseline case. In that case, the net heat input into the steam stripping is calculated to be 0.18 MJ/MJ EtOH for a 1% reference case (Luo *et al.*, 2010). As noted above, the process heat requirement is driven by the initial concentration of ethanol.

Compression Processes

Steam compression is required for the stripper column and the VCD column; the compressor is electrically powered. For 1% initial concentration, the steam compression requirement for the steam stripper is between 81.56 and 101.32 kPa (*ibid*). Simulation yields 0.0051 kWhe/MJ EtOH for the VCSS compression and 0.0067 kWhe/MJ EtOH for the VCD compression, for a total of 0.0118 kWhe/MJ EtOH. Assuming electricity produced with 38% efficiency, this requires energy inputs of 0.11 MJ/MJ EtOH (*ibid*).

Final Purification from the Azeotrope to Fuel Grade Ethanol

For the molecular sieve stage, the total heat requirement is estimated to be 1-2 MJ/kg EtOH (Cho *et al.*, 2006). Luo *et al.* (2010) assume a value of 1.5 MJ/kg EtOH or 0.056 MJ/MJ EtOH. Ethanol is stored for subsequent transportation and use as a transportation fuel (Figure 4.9). In August 2015, Algenol received a fuel-grade analysis from an independent laboratory, which certified Direct-to-Ethanol® as capable of producing fuel-grade production derived from cyanobacteria (Algenol, 2017).

Figure 4.9 Ethanol storage tank with ethanol separation facility in background

Source: Authors

Process and Performance Optimisation

The key focus of ongoing R&D efforts for 3rd generation biofuels production (including algae-based fuels) is improving photosynthetic efficiency and productivity yields. Algenol's current target is to achieve 7,000 gallons ethanol/acre-year (Algenol, 2016; Algenol, 2017). This compares with typical yields for 1st generation corn ethanol of around 400 gallons/acre-year and sugarcane of around 1,000 gallons/acre-year. The absolute theoretical limit (8 photons per C fixed) is around 30,000 gal/acre-year of ethanol (or approx. 90 g/m^2-day of biomass) with average US solar radiation (Algenol, 2016).

Between 60-90% of the net fixed carbon in Algenol's production strains is partitioned into ethanol; taking into account respiration and decarboxylation, about 80% of fixed carbon is diverted to the ethanol pathway (*ibid*). Potential yield limitations noted by Algenol include the ethanol branching ratio, light (photosaturation, photoinhibition), contaminants and the CO_2 and/or nutrient supply.

Algenol's progress report to the US Department of Energy (Algenol, 2017) describes the following key areas of ongoing process improvement:

- *Organism development* (i.e. development of algal strains optimised to location, seasonal variation to enhance photosynthesis and carbon fixation rates)

- *PBR development* (i.e. development of PBR materials, design and layout and optimised for productivity, operation and maintenance, and cost-effectiveness)
- *Process engineering* (i.e. optimising plant and process design to minimise energy and materials consumption per unit of fuel output)

4.5 Weyburn-Midale project: CO_2-Enhanced Oil Recovery

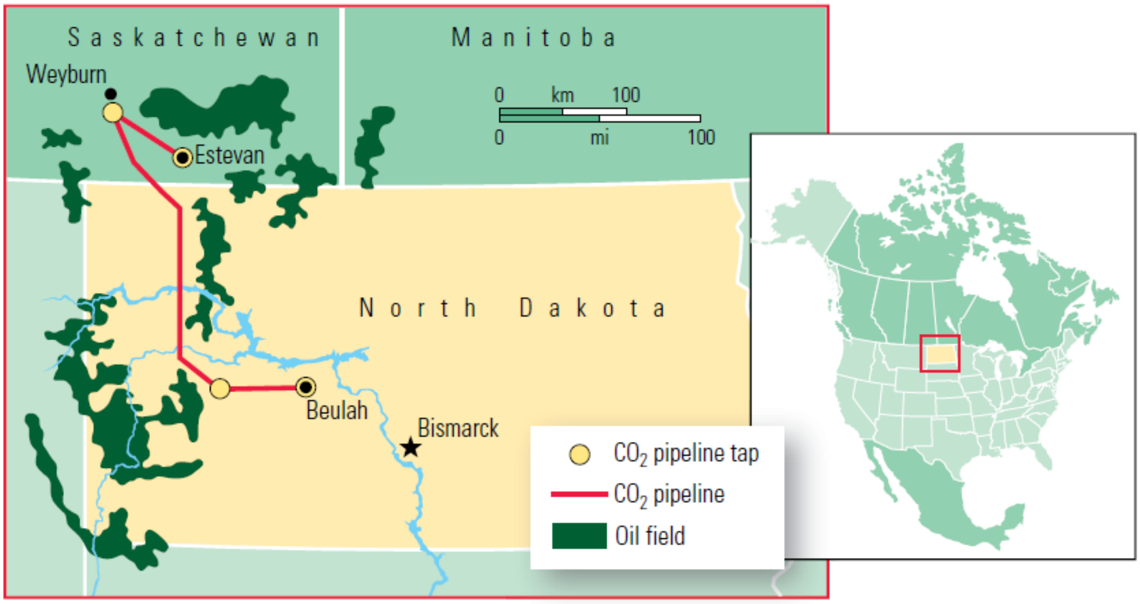
4.5.1 Overview

CO_2-Enhanced Oil Recovery (CO_2-EOR) is the process of increasing the amount of crude oil that can be recovered by injecting CO_2 into an existing depleted oil reservoir to increase pressure and reduce the viscosity of the oil. In a suitable reservoir, using CO_2 for EOR can lead to recovery of another 5% to 15% of incremental oil (Wong *et al.*, 2013). CO_2-EOR can be combined with geological storage to achieve significant net CO_2 reductions (or "CO_2 avoided") when compared with other types of conventional and non-conventional oil production.

The Weyburn-Midale field, discovered in 1954, is located in southeast Saskatchewan, Canada (Figure 4.10). Cenovus Energy Inc. currently operates the Weyburn facility on behalf of 24 partners (Cenovus, 2017). The field covers 180 km^2 and is one of the largest medium-sour oil reservoirs in Canada (Ansarizadeh et al., 2015). CO_2-EOR operations began in 2000 to reverse a long-term production decline and to demonstrate large-scale geologic storage of CO_2, and the project has become recognized as the world's largest geological CO_2 storage project. The Dakota Gasification Company operates a synfuel plant in Beulah, North Dakota that generates natural gas from coal; the by-product CO_2 produced at the plant is compressed to 15 MPa and transport 340 km via pipeline to the Weyburn-Midale field. Deliveries of CO_2 from the Beulah plant vary from 6,000 to 8,500 tonnes per day. The nearby Boundary Dam CCS project operated by SaskPower supplies an additional 2,300 tCO_2 per day to the field (*ibid*).

CO_2 storage began in September 2000 in a limited area of the field. This early phase of the operation had 16 vertical and 13 horizontal injection wells (*ibid*). A study of this injection area has been undertaken to address technical aspects of long-term geological storage. CO_2-EOR and geological storage have been successfully demonstrated at the field, potentially extending its operational period by more than 25 years. The field currently produces about 26,000 bbl/day of light crude oil; CO_2 injection has tripled oil production from the estimated lowest production rate for the field, about 8,000 bbl/day in 1988 (*ibid*). Cenovus injects approximately 2 million tonnes of new CO_2 at Weyburn every year; in total, more than 30 million tonnes of CO_2 have been injected since 2000 (Cenovus, 2017). It is estimated that about 55 million tCO_2 will be stored over the life of the project (Ansarizadeh *et al.*, 2015).

Figure 4.10 Weyburn-Midale project



Source: Ansarizadeh et al. *(2015)*

4.5.2 Description of CCU Process

The Weyburn-Midale project's infrastructure includes a central oil treating battery with multiple satellites, an extensive network of pipelines and a natural gas liquids (NGL) plant with capacity to process 12 mmcf (million cubic feet) per day of produced natural gas, yielding more than 700 bbl/d of NGL liquids (Cenovus, 2017). On-site operations include injecting, producing, recycling, and processing the CO_2 and emulsion along with flaring, venting and other onsite emission sources associated with oil production e.g. combustion of natural gas used to run crude oil emulsion treaters and other process heaters (*ibid*).

When CO_2 is delivered to the oil field for EOR, it is injected into the reservoir. The CO_2 is injected as a liquid under pressure, turning to a supercritical fluid in the reservoir as temperature increases (Wilson *et al.*, 2007). Supercritical CO_2 acts as a solvent, dissolving the residual oil, reducing viscosity, increasing its flow characteristics, and allowing it to be pumped out of the reservoir. Some of the CO_2 and water (where injected with CO_2) are carried along with the produced oil. CO_2 and water are then separated from the oil; the CO_2 is compressed and re-injected into the reservoir. This process is called CO_2 recycling. Recovered water is treated and also re-injected into the reservoir. The CO_2 that does not get produced with the oil is stored in the reservoir (CO_2 storage) (*ibid*).

The productivity of an EOR field, i.e. the amount of barrels produced per CO_2 input, is based on the amount of CO_2 injected and *not* the CO_2 brought to site. The amount of CO_2 "brought to site" is new CO_2 delivered to the EOR site from the capture facility. This arrives at injection pressure and is delivered into the reservoir through the injection wells. The amount of CO_2 "injected" is the total volume of CO_2 that is injected into the reservoir at a given time. This volume of CO_2 injected is a combination of new CO_2 (CO_2 brought to site) and recycled CO_2. Recycle CO_2 is the volume of CO_2 that returns to surface with the oil-water emulsion from the production well. The CO_2 is separated from the oil and water and then re-compressed to injection pressure where it is then re-injected to produce additional oil. The amount of injected CO_2 can be multiple times more than the amount of CO_2 brought to site (Wong *et al., 2013*).

Based upon Government of Saskatchewan Regulatory Filings for on-site fuel use at Weyburn-Midale (Government of Saskatchewan, 2017) and data provided in Ansarizadeh *et al*. (2015), as well as lifecycle GHG analysis undertaken by Wong *et al., 2013* and additional assumptions made by the authors, facility level emissions can be characterised for use in the calculation of GHG benefits arising from CO_2-EOR (see Section 5).

Process and Performance Optimisation
Certain metrics are typically collected to evaluate the performance and operational characteristics of CO_2-EOR operations. The site characteristics that are often most relevant to CO_2-EOR performance are the *Performance Ratio* and *Recycle Ratio*, which are defined as (*ibid*):

- *Performance Ratio* (units: barrels of oil produced/tCO_2 injected): The ratio of produced oil to the total volume of CO_2 injected over a given timeframe. The total volume of CO_2 required to produce oil can change, based on the reservoir characteristics, injection pressures and several other factors. This is also the total volume of CO_2 injected that can change in composition between recycled and new CO_2
- *Recycle Ratio* (units: tonnes recycled CO_2 injected/total volume of CO_2 injected): The ratio between the volume of new CO_2 brought to site and the volume of CO_2 that is recycled at any given time in the operational lifespan. The recycle ratio tends to change over the life of a project as initially the total injected volume of CO_2 is new CO_2 delivered from the capture facility, yet as greater volume of CO_2 begins to come back up the production wells with the oil and is then recycled, the recycled CO_2 begins to displace the new CO_2 and the ratio increases.

These metrics can range based on a number of factors such as field operating pressure, reservoir characteristics and the maturity of a project.

4.6 Summary

A summary of the case studies is presented in Table 4.2. Several high-level initial findings can be drawn from the analysis and through discussions with CCU operators:

- *CCU activities with potential GHG benefits are currently limited in scale*. Excluding those commercial activities such as CO_2-EOR which make use of CO_2 for enhanced commodity production only, CCU projects are currently small-scale (e.g. utilising hundreds or thousands of tCO_2 per year) in comparison with other GHG mitigation technologies.
- *Potential GHG benefits are proven but are highly dependent on circumstances*. The case studies claiming net GHG reduction benefits have been able to demonstrate the capacity to deliver real emission reductions. However, as discussed further in Section 5, it is clear that these are highly predicated on certain conditions. For example, the highly electro-intensive production process for CRI's ETL technology means that GHG benefits are contingent on the availability of a reliable low-carbon electricity source at a suitable price. The scale-up potential of CCU may be constrained by such niche conditions and limit the ease of replicability for some technology applications.

- *MRV of facility-level energy and carbon flows is well established*. Current procedures and systems for the MRV of energy, material and carbon flows at all facilities are advanced and adequate to meet requirements under most regulatory support schemes. Operators are undertaking high quality MRV across their sites as part of R&D and/or commercial activities and have an extremely high level of data handling and analysis. In respect of *site-level* energy and carbon flows, MRV requirements for most GHG reduction schemes (both economic and non-economic instruments) would pose few, if any, technical challenges to operators.[1]
- *GHG reduction policy is not yet a major driver for CCU activities*. Notwithstanding the potential for the scale-up of CCU technology to deliver real and significant GHG benefits, emission reduction incentives are not significantly driving CCU activities. CCU-derived fuels production remains at demonstration stage subject to increased incentives and/or proven economics, whilst for mineralisation and CO_2-EOR, the commercial drivers for the activities are not at all related to climate policy; CO_2 supply is effectively an operational cost.

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[1] Given the at present limited scale of most CCU projects, a larger challenge would likely relate to the administrative burden associated with carbon scheme regulation

Table 4.2 Summary of CCU case studies

Area	CRI Renewable methanol	Carbon8 mineralisation	Algenol biofuels	Boundary Dam-Weyburn CO_2-EOR
Process	Production of methanol from hydrogenation of CO_2, based on water electrolysis and zero-carbon geothermal electricity source	Production of aggregate from waste thermal residues and CO_2 feedstock via accelerated carbonate mineralisation	Production of ethanol fuel from cultivation of blue-green algae utilising CO_2 feedstock, salt-water, sunlight and nutrients	Increased production of crude oil by injecting CO_2 into an existing depleted oil reservoir to increase pressure and reduce viscosity of oil
Source of CO_2 input	Naturally occurring CO_2 from adjacent geothermal power plant	Pure CO_2 source (bought in)	Pure CO_2 source (bought in)	Coal-fired power plant and coal gasification facility
GHG abatement effect(s)	Displacement of fossil-based transport fuels; low GHG intensity of production	Permanent storage of anthropogenic CO_2 in aggregate; low GHG intensity of production	Displacement of fossil-based transport fuels; low GHG intensity of production	Permanent geological storage of CO_2
Applicability and scale-up potential	Methanol market is large. Can be applied to various CO_2 sources although GHG benefits subject to GHG intensity of electricity source	Limiting factor is availability of APCr waste material: moderate potential for scale-up and wider applicability	Biofuels market in US is large and growing. Multiple CO_2 sources could be used; limiting factor is economic production	EOR undertaken on commercial basis in North America and elsewhere subject to CO_2 availability and oil production economics
On-site energy use	Mainly electricity for hydrolysis	Electricity only	Electricity and heat (natural gas)	Electricity and fossil fuels
Key CO_2 emission sources	Indirect emissions associated with steam and electricity supply; direct venting of CO_2 during purge	Indirect emissions associated with electricity supply	Indirect emissions associated with electricity supply; direct emissions from fuel gas combustion and minimal CO_2 losses (venting)	Indirect emissions associated with electricity supply; direct emissions from fuel gas combustion and venting, flaring and blowdowns
MRV considerations	Few: site-level energy and material flows, CO_2 inputs and product outputs measured to high degree of accuracy	Few: site-level energy and material flows, CO_2 inputs and product outputs measured to high l degree of accuracy	Few: site-level energy and material flows, CO_2 inputs and product outputs measured to high degree of accuracy	Energy and CO_2 flows MRV to regulatory requirements: storage entails additional MRV requirements
Commercial drivers	Sale of methanol for fuel/blending	Avoidance of waste disposal charge (especially tax)	Pre-commercial pilot stage only	Incremental oil production
Key market and economic challenges	Recognition of CCU-derived fuels within European renewable policy	Strong competition with existing products; supply of waste (APCr) feedstock	Proving economics of production compared to other biofuels	High prices of CO_2 (or lack of supply) and low crude oil prices
GHG policy incentives	Limited at present (carbon taxes); discussions around inclusion within FQD/RED currently in progress	None at present; product branded as low-carbon product	US DOE funding and range of federal and state financial incentives	US and Canada incentives for CO_2-EOR with geological storage

5 COMPOSITE LIFE CYCLE EMISSIONS ASSESSMENT

5.1 Overview

This section builds upon the facility level GHG emissions inventory developed in the case study analysis (Section 4) by using the information gathered thereunder alongside other secondary information and data to establish an estimate of the life cycle GHG emissions inventory for CCU processes. Assumptions and information relating to the emissions performance of equivalent non-CCU products are used to determine the potential GHG benefits arising from CCU.

The results are presented as a synthesized set of findings for each CCU-derived product type, namely: methanol, aggregates, algal fuels and CO_2-enhanced oil recovery (CO_2-EOR) covering the following:

1. GHG intensity calculation and estimation of GHG benefits; and
2. Sensitivity analysis in order to understand the role played by key factors such as e.g. source of CO_2, carbon intensity of electricity supply, on-site energy use and choice of reference product, in determining GHG outcomes.

5.2 Methodology

5.2.1 Approach and Scope

The methodology involves two components: firstly the establishment of specific GHG emissions occurring across the CCU-derived product value chain and the estimated GHG intensity of CCU-derived products; and, second, the estimation of net GHG benefits. From a life cycle analysis (LCA) perspective, the methodology therefore involves both:

> *An attributional approach*: whereby system-wide GHG emissions for a particular CCU-derived product can be appropriately accounted for (life cycle GHG emissions inventory (LCI) accounting); and,
>
> *Comparative and consequential elements*: whereby potential system wide impacts can be measured, based on assuming the substitution and displacement of conventional products by CCU-derived products (GHG benefit estimation).[1]

The methodology adopted for the first component draws on internationally-recognised best practice including:

> **BSI PAS 2050:2011** *Specification for the assessment of the life cycle greenhouse gas emissions of goods and services* (BSI, 2011);
>
> **WRI/WBCSD GHG Protocol** – *Product Life Cycle Accounting and Reporting Standard* (WRI/WBCSD, 2011);
>
> ***The ILCD Handbook*** (JRC, 2012)

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[1] Excluding economic analysis.

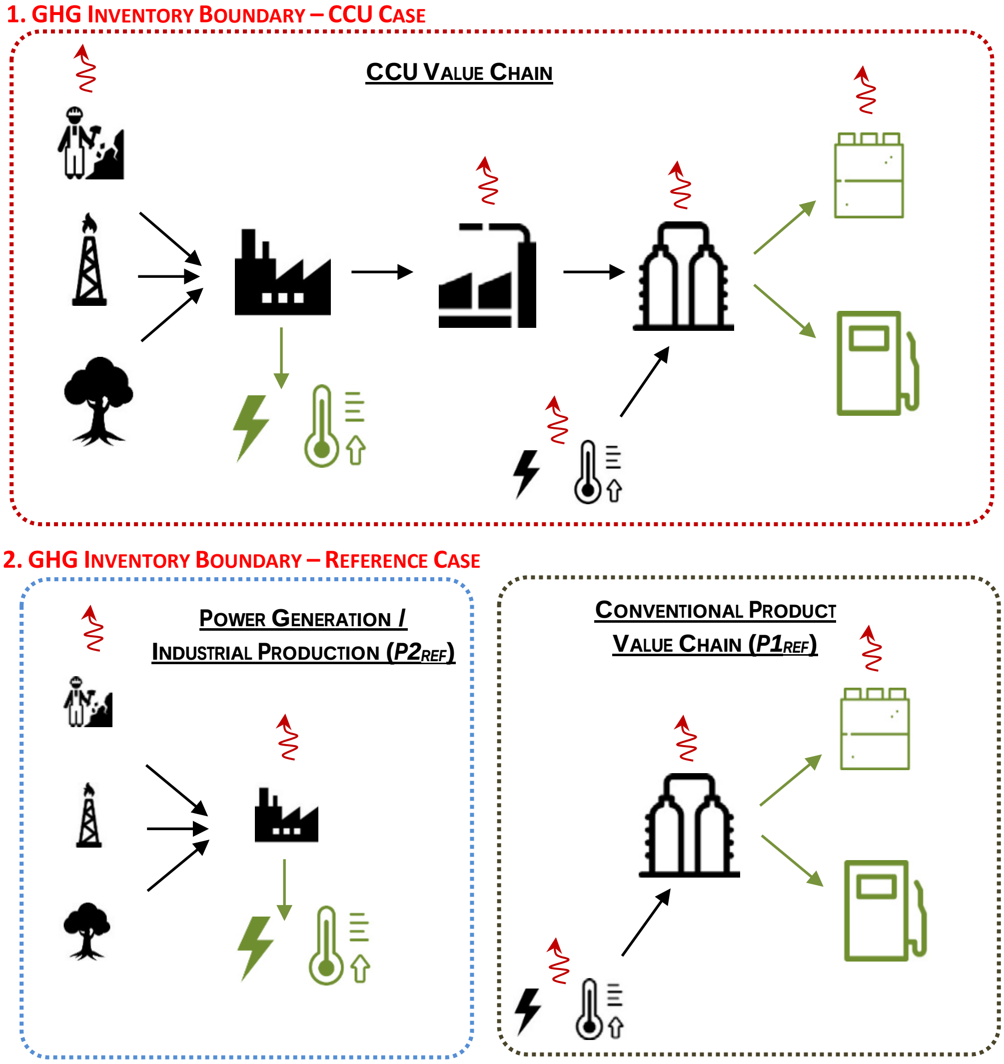
***UNEP** Global Guidance Principles for Life Cycle Assessment Databases* (UNEP, 2011)

The second component, net GHG benefits, are based on the comparison of the system on a multi-functional basis taking account of:

- The primary CCU derived product (*P1*); and
- The secondary product or service (*P2*) produced by the facility from where the CO_2 was sourced.

A systems expansion approach is employed to take into account all system outputs, namely *P1* product, *P2* product and the CO_2 produced by the *P2* facility, for the purposes of comparison with conventional products (Figure 5.1).

Figure 5.1 System boundaries for estimating net GHG benefits of CCU



Note: In the CCU case (top), three products/services are provided: (1) the CCU product; (2) the power or industrial product, and (3) the CO_2. To make a fair comparison with a conventional product, emissions from providing service (2) must also be included in the comparison ($P2_{REF}$), albeit from a smaller sized plant power plant that delivers the same level of service but without the energy penalty associated with CO_2 capture (illustrated by the smaller power plant and fuel icons in the lower left box).

Furthermore, an avoided burden method (e.g. UNEP 2008; UNEP, 2011; von der Assen, 2015) is employed to assess and manage the net GHG benefits associated with the co-production of the *P2* product, according to the left half of Figure 5.1 above. The avoided burden method – referred to hereafter as the 'CO_2 capture benefit' – is based on the relative performance of the *P2* facility with and without CO_2 capture. The CO_2 capture benefit is therefore calculated from the avoided emissions (tCO_2)[1] per tonne CO_2 captured. It thus shows the embedded CO_2 reductions contained in each tCO_2 sent for utilisation. Pre-calculated CO_2 capture benefit factors are presented in Section 5.2.2 below.

The CO_2 capture benefit approach is considered advantageous for the following reasons:

- It improves the transparency of accounting methods by handling the emission reductions benefits of CO_2 capture and utilisation separately and independently of any particular CCU product value chain;
- It reduces the complexity of comparative LCA accounting methods by reducing the inherent benefit of capturing CO_2 for utilisation into a single data point;
- It allows for a direct comparison to be made between alternative fabrication methods without including the additional complexities of considering CO_2 capture (i.e. simple gate-to-gate comparison), to which the CO_2 capture benefit can be added according to the inherent benefit assumed to be present in the CO_2 utilised (according to a 'CO_2 capture benefit factor'). This also allows for such benefits to be systematically analysed independent of product type, thereby allowing comparisons be more readily made across a range of products;
- It provides insights into issues around impermanent CO_2 storage in CCU-derived products by providing an indication of the residual GHG *liabilities* associated with each tCO_2 re-emitted upon product use.[2] This is a particularly useful addition to the analytical toolbox since this is often an area of contention in debates regarding emission reductions and CCU;
- It reduces the methodological burden on stakeholders wishing to estimate the overall benefits or otherwise of CCU processes. Without the use of such a factor, it is necessary to undertake systems expansion for every assessment, involving collection of emissions for both the CO_2 source facility and comparable product, and to also make assumptions regarding the CO_2 source and the relevant reference case in order to calculate the net GHG benefits of a CCU product;
- It allows an assessment to be made of the potential range of overall product GHG emission reduction benefits in situations where there is incomplete knowledge about the source of CO_2 and the possible range of reference cases.

The full details of the approach are set out in the report: *Greenhouse Gas Accounting Guidelines for CCU v1.0*, which is presented as a stand-alone guideline for use in estimating GHG emissions

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[1] Avoided emissions equals the difference in GHG emissions intensity per unit of P2 output between a plant with and without capture

[2] The residual liability for such emissions is broadly equivalent to the reciprocal of the CO_2 capture benefit factor, assuming all other downstream sources of emissions are equal for both *P1* CCU and reference cases.

and GHG benefits of employing CCU. They are therefore excluded here, and the reader is referred to those guidelines for more information.

5.2.2 CO_2 Benefit Factors

CO_2 benefit factors have been calculated for various combinations of CO_2 source and reference plants using secondary data sources relating to the technical performance of power generation and industrial facilities with and without CO_2 capture and assessments of upstream fuel emissions (as summarised in Table 5.1 below).

Table 5.1 Information sources used to calculate CO_2 capture benefit factors

Area	Item	Sources of Information
Capture and Reference Capture Plant type	Power plants	GCCSI (2011); McKinsey & Co. (2008)
	Biomass power plants	ETI (2012)
	Iron and Steel	IEA GHG (2013)
	Cement	IEA GHG (2008a); IEA (2008)
	Ammonia (high purity CO_2)	IEA GHG (2008b); IFA (2009)
	Direct air capture	Baciocchi (2006); APS (2011)
	Others	IPCC (2006)
Upstream Fuel Emissions	Natural gas	UNFCC (2012)
	Coal	UNFCC (2012)
	Biomass	AECOM (2010)
	Petroleum Coke	Moretti *et al.* (2017)

In some cases the secondary data have been adjusted *pro rata* to ensure that the output of the reference plant is suitably matched to that of the source plant. The results of these calculations for power plant cases are shown in Table 5.2. The bold text in the table presents the CO_2 benefit factor for cases where the reference plant equates to the equivalent CO_2 source plant without CO_2 capture. All other cases are variants of these. The results for industrial plants and direct air capture (DAC) are shown separately at the bottom of the table.

The CO_2 benefit factors simply reflect the well-founded principle in CO_2 capture of *avoided emissions*, although they offer a novel way of looking at CCU technologies. What the factor shows is the inherent GHG emission reduction benefit of using 1 tonne of captured CO_2, which is conceptually useful for understanding the GHG benefit of CCU technologies. For example, if a CCU process utilises 1,000 tonnes per year of CO_2 captured from a natural gas combined cycle plant (NGCC), *and* the reference case is assumed to be a an unabated NGCC *and* all downstream emissions (processing and use) are equal to that of a conventional product, then the emission reduction is 83% or 830 tonnes CO_2 per annum. This applies regardless of whether the sequestration in the product is permanent or impermanent. In the case of the latter, this seems counterintuitive, but is correct because the emissions arising from CCU product use are netted out against the same emissions from use of a conventional non-CCU product; thus the GHG emission reduction benefits arising at the capture plant still apply irrespective of the fact that the CO_2 was re-emitted. For example, if the downstream emissions from the combustion of a

CCU-derived fuel are 500 tCO_2 for every 1,000 tCO_2 utilised, then these same 500 tCO_2 emissions would also be emitted by the equivalent conventional product, meaning the 830 tonnes CO_2 emission reduction upstream still applies. This is a particularly useful lens through which to view CCU technologies.

Table 5.2 CO_2 benefit factors for various *Source* and *Reference* plant combinations

		CO_2 source plant					
		Biomass + capture	IGCC + capture	NGCC + capture	PC supercritical + capture	Supercritical 2 + capture	Ultra-supercritical + capture
Reference plant	Biomass (or other RE)	**0.99**	-0.17	-0.11	-0.16	-0.16	-0.16
	IGCC	2.15	**0.79**	1.93	0.59	0.61	0.75
	NGCC	1.53	0.27	**0.83**	0.18	0.19	0.26
	PC supercritical	2.23	0.86	2.07	**0.64**	0.66	0.82
	Supercritical 2	2.22	0.04	2.06	0.64	**0.66**	0.81
	Ultra-supercritical	2.08	0.73	1.80	0.54	0.56	**0.70**
	Biomass + capture	0.00	-1.00	-1.16	-0.81	-0.82	-0.94
	IGCC + capture	1.20	0.00	0.25	-0.03	-0.02	0.01
	NGCC + capture	1.06	-0.12	0.00	-0.12	-0.12	-0.11
	PC supercritical + capture	1.24	0.04	0.33	0.00	0.01	0.04
	Supercritical 2 + capture	1.23	0.03	0.31	-0.01	0.00	0.03
	Ultra-supercritical + capture	1.19	-0.01	0.24	-0.03	-0.03	0.00

CO_2 source plant	Ammonia + capture	Cement + capture	Steel mill + capture	DAC (100% renewable)	DAC (natural gas)	DAC (coal)
Reference plant	Ammonia	Cement	Steel mill			
Benefit factor	0.94	0.67	0.84	0.54	0.30	0.13

5.3 Renewable Methanol

5.3.1 GHG Benefit

The calculated GHG intensity levels for the renewable methanol and non-CCU reference product are shown in Figure 5.2, along with the net GHG benefit arising from using CCU. The example shown assumes capture and utilisation of CO_2 from a natural gas combined cycle (NGCC) power plant.

In the figure, facility-level and end use emissions are shown as a positive value. The facility-level emissions for the renewable methanol are calculated from the site-level data[1]; emissions for a conventional methanol plant are based on best available steam methane reforming (SMR) in Europe (Perez-Fortes *et al.*, 2016). End use emissions assume full combustion of methanol fuel, resulting in release of CO_2 to the atmosphere.

The GHG benefit arising from the *avoided emissions* at the power plant in the CCU case is shown as a GHG reduction i.e. a negative value. This includes calculation of the additional upstream fuel emissions (e.g. from fuel extraction and processing) arising from the capture process 'energy penalty'. To calculate the GHG intensity of the renewable methanol product, this benefit (the 'CO_2 capture benefit') must be netted off against the facility and end use emissions. The resulting net emissions are shown, demonstrating a significant associated GHG benefit when compared to conventional SMR methanol.

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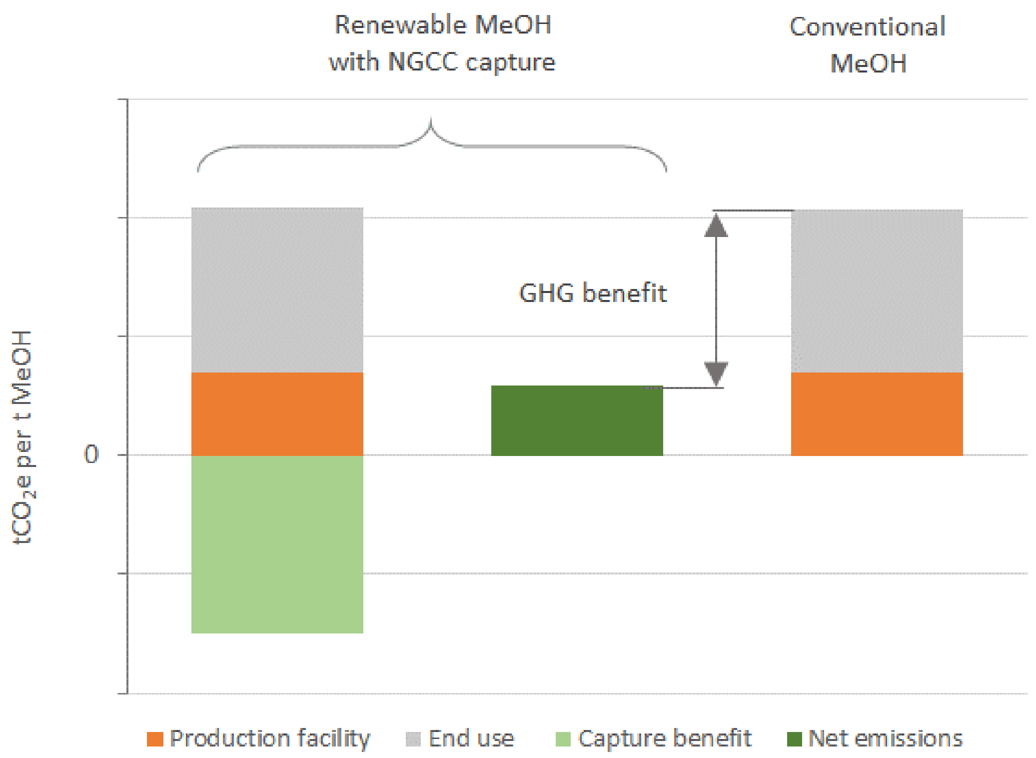
[1] It should be noted that the facility level emissions include *re-emitted* CO_2 from the captured CO_2 source.

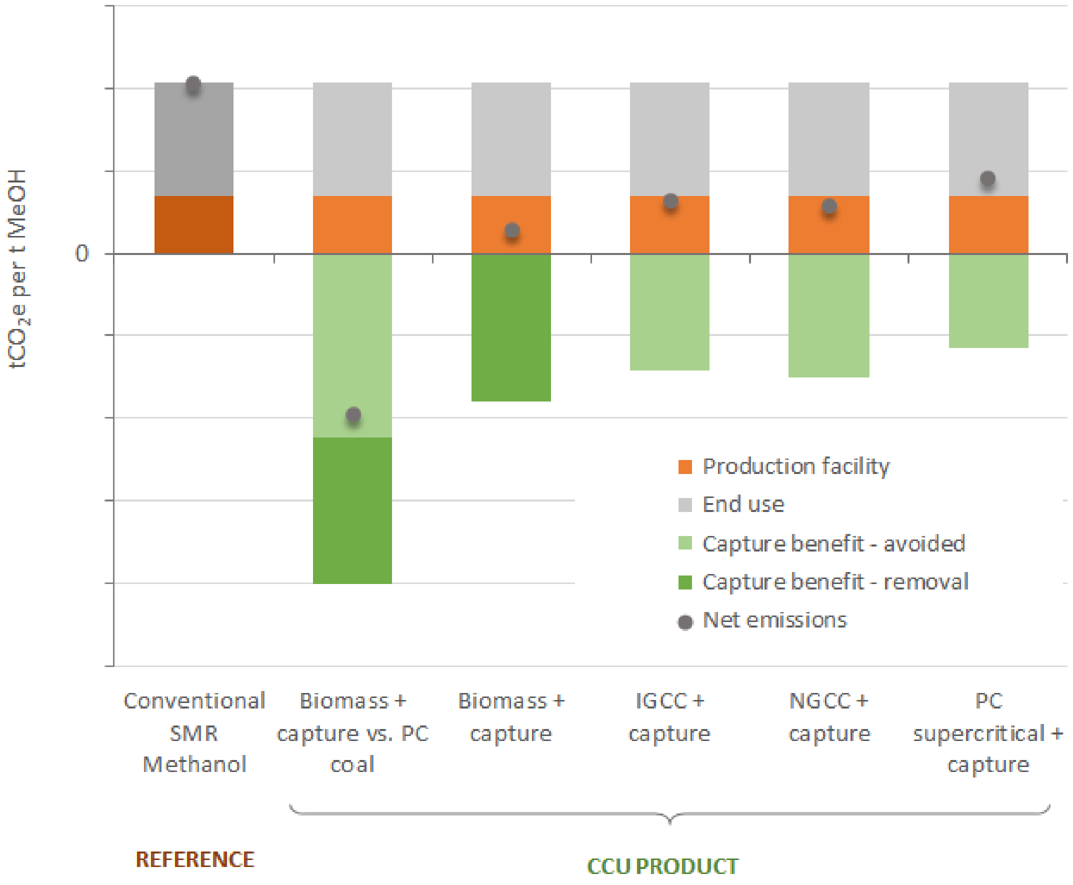
Figure 5.2 GHG benefit from renewable methanol with NGCC CO_2 capture versus conventional SMR methanol



5.3.2 Sensitivity

Figure 5.3 shows the GHG emissions intensity for renewable methanol production compared to the reference non-CCU product (conventional SMR methanol) according to different CO_2 capture and reference plants. As described above, the CO_2 capture benefit varies according to the chosen power plant technology in the CCU and reference cases. The results show a significant GHG benefit compared to the reference case in all cases. This is most pronounced in the case of biomass with capture compared to unabated coal-fired power, and least pronounced in the case of pulverised coal with and without capture. In the former case, there is a so-called ‘double-dividend’ net GHG reduction involving a CO_2 removal from atmosphere (during biomass growth) and the avoidance of fossil fuel emissions (from the reference coal-fired power plant).

Figure 5.3 GHG comparison of renewable methanol production utilising different sources of CO_2 (capture from power plants)



Note: unless shown, reference power plants are the equivalent capture plants without capture

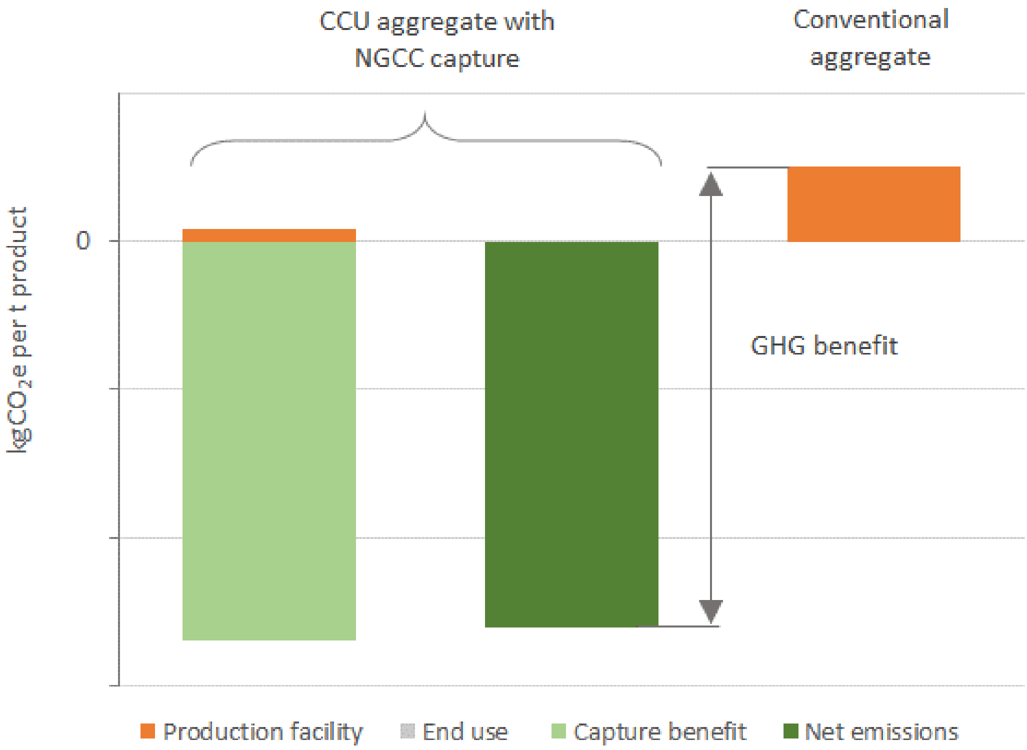
5.4 Carbonate Mineralisation

5.4.1 GHG Benefit

The calculated GHG intensity values for the renewable methanol and non-CCU reference product are shown in Figure 5.4, along with the net GHG benefit arising from employing CCU.

In the figure, the facility-level emissions are shown as a positive value. The facility-level emissions for the CCU aggregate are calculated from the site-level data; emissions for conventional aggregate production are based on lifecycle assessment data for general aggregates (University of Bath, 2017). The GHG benefit arising from the *avoided emissions* at the power plant in the CCU case is shown as a GHG reduction. To calculate the GHG intensity of the CCU aggregate product, the CO_2 capture benefit must be netted off against the facility emissions. The resulting net GHG emissions are shown, demonstrating an associated GHG benefit of around six times the GHG intensity of the conventional reference product.

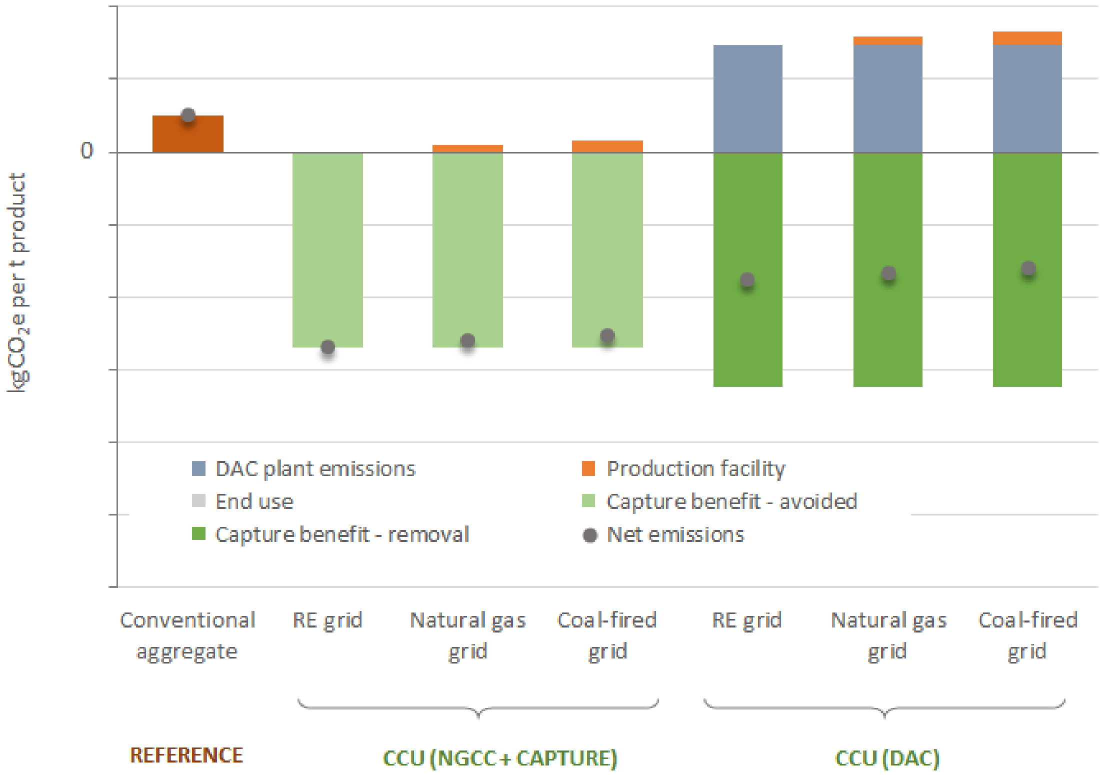
Figure 5.4 GHG benefit from CCU aggregate with NGCC CO_2 capture versus conventional aggregate



5.4.2 Sensitivity

Figure 5.5 shows the effect of electricity grid intensity on the life cycle GHG inventory of the CCU-derived aggregate product. Results are shown for capture from an NGCC plant and from DAC; in the latter case, direct and indirect emissions arising from DAC equipment energy use are shown as positive emissions sources which must be netted off the associated CO_2 removals. It can be seen that there is a significant benefit in all cases, reflecting the fact that the carbonate mineralisation production process is not electro-intensive (per unit of product output), and therefore indirect electricity emissions are not a key factor determining overall GHG product performance.

Figure 5.5 GHG comparison of CCU aggregate with varying carbon intensity of on-site electricity supply



Note: DAC plant is based on a renewable electricity supply

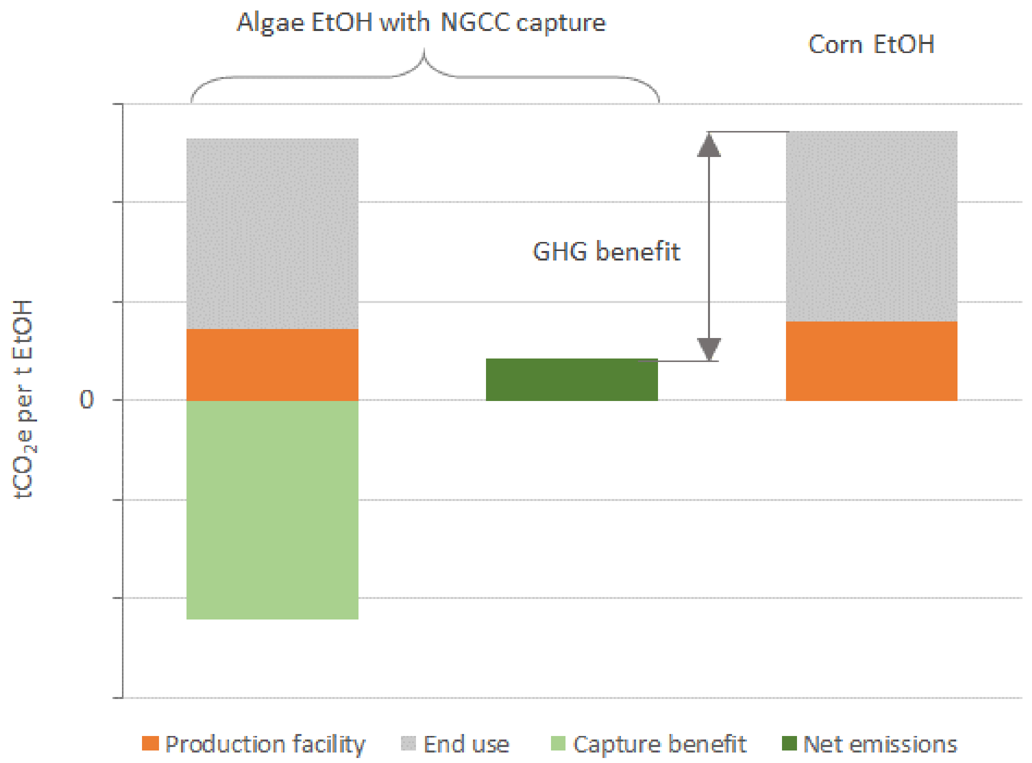
5.5 Algae-Based Ethanol

5.5.1 GHG Benefit

The calculated GHG intensity values for the algae-based ethanol and non-CCU corn ethanol are shown in Figure 5.6, along with the net GHG benefit arising from employing CCU.

In the figure, the facility-level and end use emissions are shown as a positive value. The facility-level emissions for the algal ethanol are calculated from the site-level data; emissions for the reference product are based on lifecycle assessment data for corn ethanol production in the US (Mueller, 2016). End use emissions assume combustion of ethanol fuel resulting in release of CO_2 to atmosphere. The GHG benefit arising from the *avoided emissions* at the power plant in the CCU case is shown as a GHG reduction i.e. a negative value. To calculate the GHG intensity of the algae-based ethanol product, the CO_2 capture benefit must be netted off against the facility and end use emissions. The resulting net emissions are shown, demonstrating a significant associated GHG benefit from CCU when compared to corn ethanol.

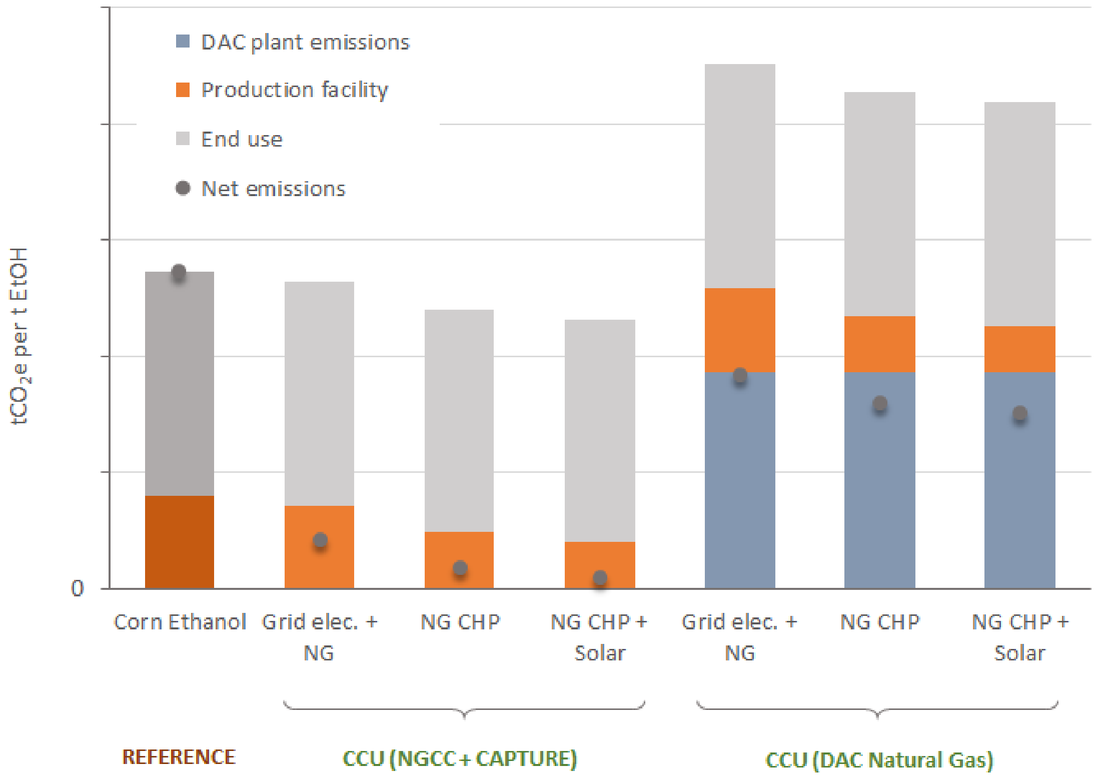
Figure 5.6 GHG benefit from CCU algae-based ethanol with NGCC CO_2 capture versus corn ethanol



5.5.2 Sensitivity

Figure 5.7 shows the effect of different on-site energy configurations on the life cycle GHG inventory of algae-based methanol, and the associated net GHG benefit compared to corn ethanol. The results show that facility emissions per unit of product output can be significantly reduced through use of combined heat and power (CHP) and solar energy to replace the base case assumption of grid-based electricity supply and on-site natural gas combustion. Whilst this results in an overall reduction in GHG intensity, the net effect is marginal due to the much larger contribution of end use emissions.

Figure 5.7 GHG comparison of algae-based ethanol according to different on-site energy configurations



Note: For reasons of scale, the negative value capture benefits are not shown

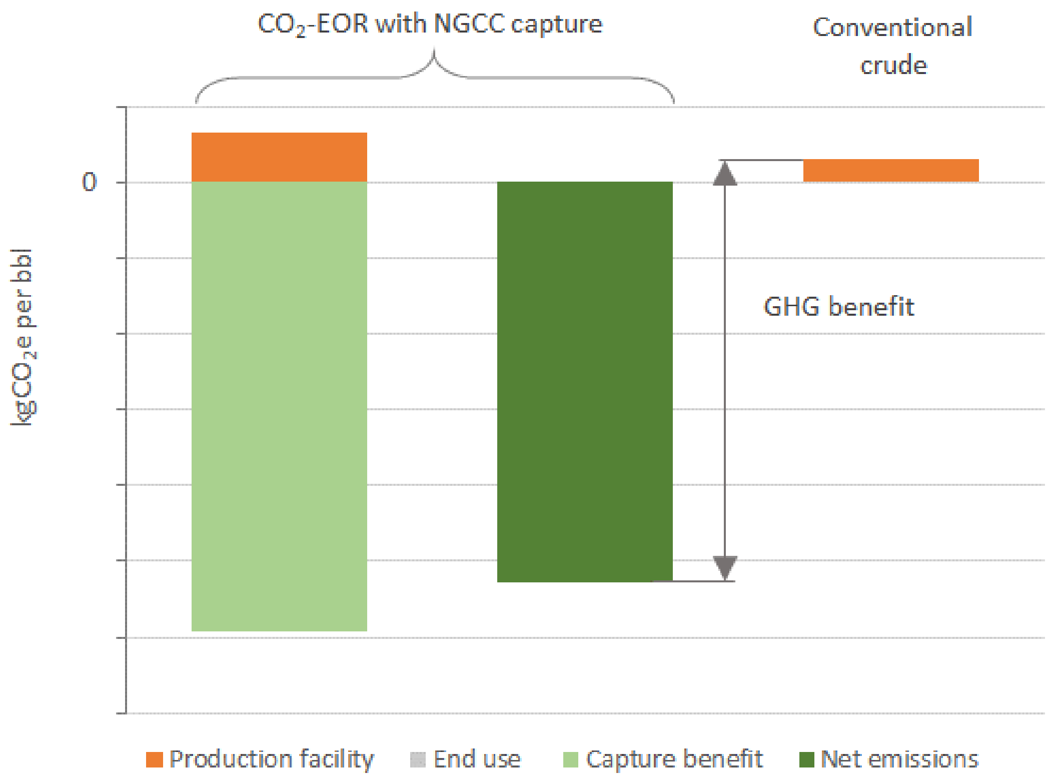
5.6 CO_2 Enhanced Oil Recovery

5.6.1 GHG Benefit

The calculated GHG intensity values for the CO_2-EOR and conventional crude oil are shown in Figure 5.8, along with the net GHG benefit arising from CCU employment.

In the figure, the facility-level emissions are shown as a positive value. The GHG benefit arising from the *avoided emissions* at the power plant in the CO_2-EOR case is shown as a GHG reduction i.e. a negative value. To calculate the CO_2-EOR crude GHG intensity, this capture benefit must be netted off against the facility emissions. The resulting net emissions are shown, demonstrating a significant associated GHG benefit compared to conventional crude oil production.

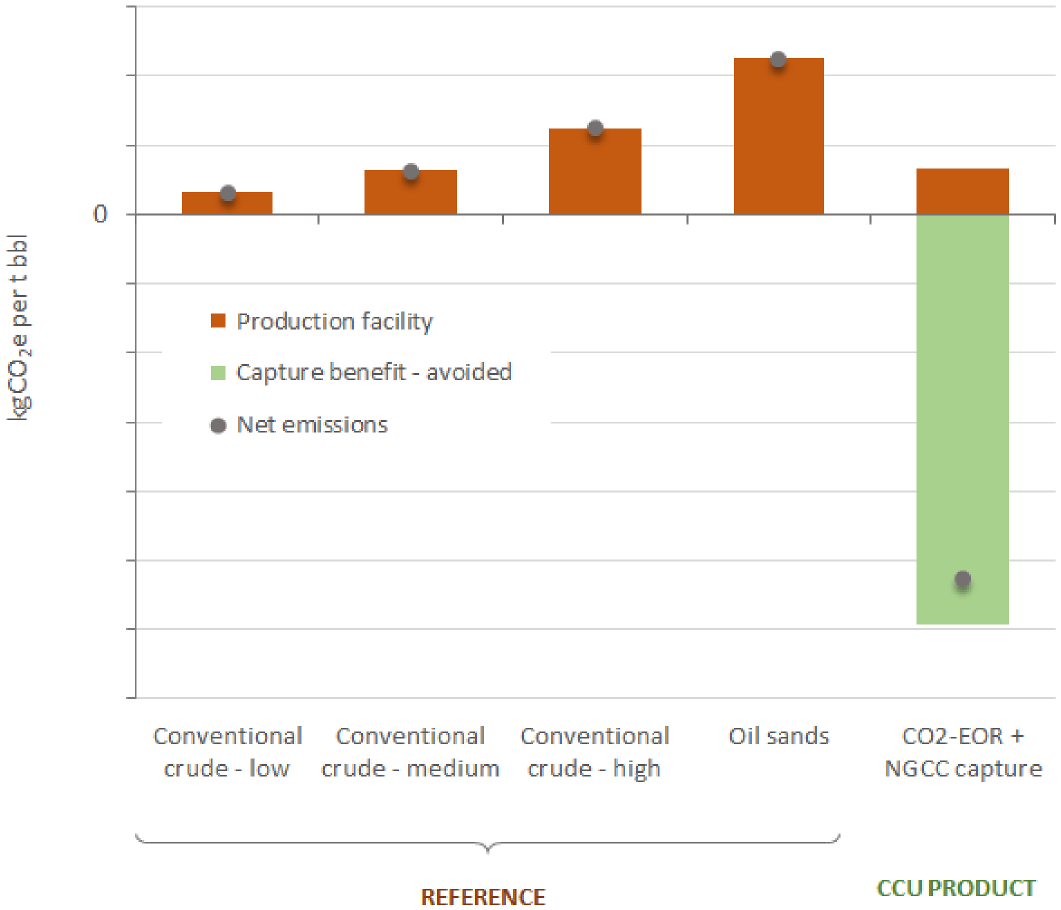
Figure 5.8 **GHG benefit from CO_2-enhanced oil production with NGCC CO_2 capture versus conventional oil production**



5.6.2 Sensitivity

Figure 5.9 shows a comparison of the GHG intensity of CO_2-EOR production compared to different types of reference product. The results show how the choice of reference product can significantly affect the scale of GHG benefit attributed to the CCU product. Although a benefit from CO_2-EOR is seen in all cases, this is most pronounced when the reference product is chosen to be (carbon-intensive) oil sands. As described earlier (Section 4.5) various other technical factors will have a significant bearing on the GHG performance of CO_2-EOR production, many of which are highly specific to the characteristics of the oil field and the nature of the CO_2 injection operations. These will affect *inter alia* the volume of CO_2 stored, the volume recycled, and the volume vented (re-emitted).

Figure 5.9 **GHG comparison of CO_2-enhanced oil production versus different types of crude oil production**



Note: Values shown for conventional crude oil and oil sands based on ICCT, 2010

5.7 Sources of Uncertainty

The sensitivity analyses presented for each of the CCU products above briefly illustrates the possible range of GHG benefit estimates arising from different choices regarding key input factors. Some of these may be well understood and established to be the case for a given project (e.g. the CO_2 capture source; on-site energy use) whereas others may be subject to an inherent degree of uncertainty (e.g. the choice and GHG intensity of the reference product). Such inputs can have a significant impact upon the accuracy of the results, including the calculation of the GHG benefit.

A common principle of most existing GHG protocols and guidelines is that uncertainty must be reduced as far as practical. Several sources of uncertainty can be identified within the analysis and calculation methodology presented in this report, covering each of the key CCU life cycle stages, i.e.:

- Upstream fuel extraction/harvesting
- CO_2 capture and reference plant (power generation or industrial facility)
- Production facility

- Product end use

These areas of uncertainty are reviewed below.

5.7.1 Upstream Fuel Extraction/Harvesting

A major source of uncertainty relates to the calculation of upstream emissions from fuel extraction. GHG emissions arising from the extraction, processing and transportation of fossil fuels (coal, gas, oil) and biomass upstream of the capture plant can be highly variable according to, *inter alia*, specific sub-fuel types, extraction technology, processing (including process efficiency and performance), geography, and various geological factors. Where a specific fuel source and/or sub-type is known to be used in the capture plant, associated emissions data should be used to enhance the accuracy of the calculation. However, given the nature of energy markets and the widespread transportation of fuels from varying sources, this is not commonly the case. In some cases, a particular fuel source may be known, for which life cycle data may be available; elsewhere, default emissions factors based on activity data (i.e. fuel consumption at the capture and reference plants) will need to be used to make such calculations.

A large number of upstream fuel emissions factors exist within the literature. Table 5.3 presents a small selection of these, demonstrating the potentially wide range within a given fuel type.

Table 5.3 Upstream GHG emissions factors for different fuel types

Fuel type		tCO_2e/TJ	Source
Natural gas	**Pipeline natural gas**	**2.9**	UNFCCC (2012)
	Liquefied Natural Gas (LNG)	16.2	
Coal	Not 100% sourced from within host country; surface mine or other	2.8	UNFCCC (2012)
	Not 100% sourced from within host country; underground	10.4	
	100% sourced from within host country; surface mine or other	**5.8**	
	100% sourced from within host country; underground	21.4	
Petroleum coke	**Petroleum coke**	**9.6**	Moretti *et al.* (2017)
Biomass	**Wood chips**	**4.1**	AECOM (2010)
	Wood pellets	10.4	

Note: values used in the analysis are shown in bold

The values used within this analysis are indicated in bold text: these values were chosen with the aim of representing a broadly representative option within each of the fuel type categories (e.g. pipeline gas over LNG gas). As can be seen, the range of values indicates the importance of the choice. For a given fuel type, the materiality of the upstream emissions – and therefore the potential level of inaccuracy – will be greatest in those cases where large amounts of CO_2 are used in the CCU process, and where the CO_2 is captured with a low efficiency and therefore high associated energy penalty.

5.7.2 CO_2 Capture and Reference Plant

The calculation of emissions, and emission reductions, arising from CO_2 capture are strongly influenced by performance assumptions of the process and also that of the reference plant. Areas of uncertainty include the accuracy and representativeness of the performance data used for the capture process (e.g. fuel consumption/heat rate; capture efficiency). More significant is the uncertainty around the choice of reference plant. In the case of capture from an industrial facility this will simply be the facility without use of CO_2 capture equipment (implicitly assuming that the unabated 'without capture' scenario is considered to best represent the reference case). This choice is less clear in the case of power generation where the functional unit (*P2*) is the same between different fuel types and generation technologies. The reference plant for power generation may also simply be considered to be the equivalent plant without CO_2 capture, although in other cases it may be considered more applicable to look at an alternative basis for choosing the most applicable reference case within a given energy market system (e.g. based on the use of grid supply, therefore requiring the use of grid-based or power system emissions factors). In the absence of perfect knowledge of the reference case, this choice, and the associated emissions performance values, represents a key assumption and source of uncertainty influencing the calculated results.

5.7.3 Production Facility

The analysis undertaken excludes GHG emissions from other elements of the CCU-derived product fabrication process, including materials consumption, water consumption, waste processing and treatment and any relevant land use impacts. This inherently means that there is uncertainty regarding the true level of GHG benefits achievable by CCU, since it is unclear whether the emissions embedded in, and arising from, these products would have material effects on the estimated GHG benefit. However, it is important to note that these are similarly excluded in the selected primary product (*P1*) reference cases used for comparison. Therefore, it is possible that they might broadly cancel each other out if included. The effort needed to resolve these issues is likely to be extensive. The advantage of the way the results have been presented in this study is that the GHG benefit shows the "headroom" into which increasing attribution of emissions to a CCU-product could be made before CCU becomes less beneficial than the conventional non-CCU product.

A similar area of uncertainty in calculating emissions at the production facility stage lies in the choice of reference product - and the representativeness/accuracy of the associated facility-level emissions performance. As with the upstream fuel use, the appropriate choice of emissions factor may be highly uncertain, particularly where multiple production processes and technologies exist to produce an equivalent functional unit (*P1*). A large number of sources can be drawn upon when assessing the emissions from reference case production facilities. Sources of uncertainty relating to the product end use stage include the use of default emissions factors for reference product fuels, as used in the current analysis, as well as (for permanent storage CCU processes) assumptions around the equivalence of the permanence of CO_2 stored in CCU and non-CCU products.

Table 5.4 shows a selection of emissions factors for reference product types, demonstrating again the wide range of emissions factors within a given product group.

Table 5.4 **GHG emissions factors for different reference products**

Product type		Value	Source
Methanol	**Steam methane reforming based on natural gas feedstock (Europe)**	**0.70 tCO_2e/t MeOH**	Perez-Fortes *et al.* (2016)
	Steam methane reforming based on natural gas feedstock (US)	0.46 tCO_2e/t MeOH	GREET (2017)
Ethanol	Ethanol from ethylene (Europe)	1.248 tCO_2e/t EtOH	Ecoinvent (2017)
	Corn ethanol (US)	0.879 tCO_2e/t EtOH	Flugge *et al.* (2017)
	Corn ethanol (US)	0.764 tCO_2e/t EtOH	EPA (2010)
	Corn ethanol (US)	**0.807 tCO_2e/t EtOH**	Mueller (2016)
Aggregates	**General Aggregate**	**0.0051 tCO_2e/t product**	University of Bath (2017)
	General Stone	0.079 tCO_2e/t product	
	General Sand	0.0051 tCO_2e/t product	
	Light Expanded Clay Aggregate (LECA)	0.16 tCO_2e/t product	LECA Products (2017)
	Land won gravel aggregates (average)	0.002155 tCO_2e/t product	WRAP (2009)
	Land won sand aggregates (average)	0.00185 tCO_2e/t product	
Crude oil	**Conventional crude: low intensity onshore**	**0.016 tCO_2e/bbl**	ICCT (2010)
	Conventional crude: medium intensity onshore	0.031 tCO_2e/bbl	
	Conventional crude: high intensity onshore	0.063 tCO_2e/bbl	
	Tar sands	0.113 tCO_2e/bbl	

Note: values used for the main results in the analysis are shown in bold

The values chosen in the present analysis are indicated in bold text; these were chosen based on a judgment of the most applicable reference option within each of the product categories (and, where multiple studies exit, based on the most 'representative' or mid-point values). A key uncertainty is the scope of the GHG intensity estimate – in many cases it is unclear whether it is cradle-to-grave, cradle-to-gate, or gate-to-gate – and also the underlying assumptions used to calculate process inputs in the case of cradle-to-gate analysis. The reference cases used in this study were selected because they offered a level of transparency that allowed the extraction of gate-to-gate analysis for comparison purposes.

As with the choice of upstream fuel emissions factors, the choice of reference product and associated emissions factor represents another important source of uncertainty influencing the calculated results.

5.7.4 Product End Use

An important area of uncertainty can arise from systemically assuming substitution and displacement of conventional products by the CCU-derived product, and specifically whether perfect substitution between the CCU and reference case product can indeed be assumed. This consideration represents another important source of uncertainty influencing the calculated GHG benefit results. Where the substitution effect is not perfect and the reference product is more carbon intensive than the CCU-derived product, then the assumption of perfect substitution will serve to over-estimate the GHG benefits of CCU.

6 CONCLUSIONS

The main findings of the research programme on CO_2 capture and utilisation technologies (CCU) are:

1. Momentum for CCU has increased significantly over recent years at a political, industrial and academic level.
2. A number of funded CCU research, development and demonstration (RD&D) projects, and several ongoing commercial operations, are active around the world at the current time.
3. Despite the various RD&D funding efforts, uncertainty remains regarding the efficacy of CCU technologies to deliver real, measurable, verifiable and scalable GHG emission reductions.
4. Asymmetry of information notwithstanding, there is growing political pressure on regulators to integrate CCU into low carbon policies.
5. Actions at a political level and the RD&D activities for CCU on the ground appear to be out of synchronisation.
6. Analyses of the energy and carbon flows across a selected number of commercial and demonstration scale CCU case studies show that there is potential for GHG benefits to arise from CCU.
7. Net GHG benefits arising from CCU technologies can only be fully assessed by taking a life cycle GHG accounting perspective.
8. The complexity of GHG accounting and net GHG benefit assessment can be reduced by employing a 'CO_2 capture benefit' method.
9. Although the analysis provides new insights into CCU GHG accounting, it is partial as it considers only energy and carbon flows across the CCU life cycle and is based only on large demonstration/commercial-scale operations. This does provide a valuable building block from which to develop more comprehensive approaches, however.
10. Based on the approach taken in this research, CCU GHG accounting guidelines v1.0 have been prepared to facilitate improved transparency about CCU and emission reductions.
11. The life cycle of CCU means that several factors must be kept in mind when designing appropriate policies and regulation.

These conclusions have been elaborated in the Summary of Findings at the front of this report.

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