ASSESSING THE POTENTIAL OF CO_2 UTILISATION IN THE UK

Final Report

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Date: 26 May 2017

Project number: SISUK17099

Reviewer: Ann Gardiner

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Acronyms

^oC	Degrees centigrade
ACT	Accelerated Carbonation Technology
AEC	Alkaline electrolysis cells (electrolyser)
APCr	Air pollution control residue
BEIS	Department for Business, Energy and Industrial Strategy
Ca	Calcium
$CaCO_3$	Calcium carbonate
CaO	Calcium oxide
$Ca(OH)_2$	Calcium hydroxide
CCS	Carbon Capture and Storage
CCU	Carbon Capture and Utilisation
CCUS	Carbon Capture Utilisation and Storage
CHP	Combined heat and power
CKD	Cement kiln dust
Cl_2	Chlorine
CNG	Compressed natural gas
CO	Carbon monoxide
CO_2	Carbon dioxide
CRI	Carbon Recycling International
d	day
DECC	Department of Energy and Climate Change
DME	Dimethyl ester
EO	Ethylene oxide
EPA	(US) Environmental Protection Agency
EU	European Union
EU ETS	EU Emissions Trading Scheme
g	Gas (used in chemical formulae)
GCC	Ground calcium carbonate
GHG	Greenhouse gas

H_2	Hydrogen
ha	Hectare
HCL	Hydrochloric acid
HVO	Hydrotreated vegetable oil
IMO	International Maritime Organization
IRENA	International Renewable Energy Agency
k	Kilo (thousand) tonne
l	Liquid (used in chemical formulae)
LEP	Local Enterprise Partnership
LPG	Liquefied petroleum gas
M5-100	Blend level of methanol in gasoline
MCI	Mitsui Chemicals Inc.
MDI	Methylene diphenyl diisocyanate
Mg	Magnesium
$MgCO_3$	Magnesium carbonate
MgO	Magnesium oxide
Mt	Mega (million) tonne
MTBE	Methyl tert-butyl ether
MTO	Methanol-to-olefins
MW	Mega watt
MWh	Mega watt hour
Na_2CO_3	Sodium carbonate (soda ash)
$NaHCO_3$	Sodium bicarbonate (baking soda)
NaOH	Sodium hydroxide
NOx	Nitrogen oxides
PCC	Precipitated calcium carbonate
PE	Polyethylene
PEC	Polyethylene carbonate
PEM	Proton exchange membrane (electrolyser)
PCHC	Polycyclohexane carbonate
PM	Particulate matter

PO	Propylene oxide
PPC	Polypropylene carbonate
PP	Polypropylene
ppm	Parts per million
PPP	Polycarbonate polyols
s	Solid (used in chemical formulae)
R&D	Research and development
RFNBO	Renewable liquid and gaseous transport fuel of non-biological origin
RTFO	Renewable Transport Fuel Obligation
SiO_2	Silicon dioxide
SOEC	Solid oxide electrolysis cells (electrolyser)
SOx	Sulphur oxides
SNG	Synthetic natural gas / Substitute natural gas
t	tonne
TDI	Toluene diisocyanate
TRL	Technology readiness level
TWh	Tera watt hour
UK	United Kingdom
US	United States
yr	Year

Executive summary

E.1 Introduction

Carbon capture and utilisation (CCU) in general is considered to involve the ***capture*** of carbon dioxide (CO_2) from either a point source (e.g. power station or industrial process), its ***transport*** and its subsequent ***use***. CCU can be applied in a broad range of applications either as part of a biological or chemical conversion process for the fabrication or synthesis of new products (e.g. building products, polymers), or in processes where CO_2 acts a solvent or working fluid in industrial processes.

CCU is already being deployed in the UK. Projects include Carbon8's[1] two plants that treat thermal wastes with CO_2 to produce an aggregate, as well as examples of CCU in horticulture. CCU is also widely applied in the food and drink sector, primarily in beverage carbonation, and to a lesser extent in food freezing, chilling and packing applications. Tata Chemical Europe's sodium bicarbonate plant at Winnington is also a major CO_2 offtaker. It is estimated that the total size of the UK market in 2016 was in the range of 400-500 ktCO_2/yr.

There is growing interest to understand the potential for CCU to reduce greenhouse gas (GHG) emissions from energy and industrial related sources, and how it may compliment CO_2 capture and storage (CCS). CCU also potentially creates valuable (low carbon) products and provides opportunities for industrial symbiosis. Furthermore, CCU may also provide both a revenue stream for carbon capture projects and reduce the exposure of industry to increasing carbon prices in the future.

There are, however, a number of challenges that make an **accurate assessment of the potential** for CCU difficult; some of these include:

1. The available evidence on the commercial potential for CCU is limited.
2. Many CCU technologies are at an early stage of development and not yet ready for commercial deployment.
3. There is a lack of robust quantitative data on potential CO_2 markets in the UK, specifically in terms of sectors and geographical location.
4. There is a lack of market research into the "green premium" that consumers would be prepared to pay for CCU products.
5. Many technologies and/or products capture CO_2 for only a short time before re-releasing it.

[1] http://c8a.co.uk/about-us/

In September 2016, the UK Department for Business, Energy and Industrial Strategy (BEIS) commissioned Ecofys and Imperial College London to assess the potential of CCU in the UK to 2030. The key objectives of this study were to:

- Examine and report on the potential of CCU in the UK to help long-term CO_2 abatement.
- Identify the most promising applications of CCU in the UK - including an assessment of the Technology Readiness Level (TRL), carbon abatement potential, most promising deployment locations and barriers that may hinder development.
- Advise on innovation support.

The project was split into three phases.

E.2 Phase 1: Evidence review of CCU technologies

The first phase consisted of a literature review to build a long list of CCU technologies for consideration in the study. In total, 25 CCU technologies were identified. These technologies were categorised as follows (a selection of technologies are listed for each category)[2]:

- **Chemicals production:** Formic acid, polymer processing
- **CO_2 mineralisation:** Carbonate mineralisation, concrete curing, novel cements
- **CO_2 to fuels carrier:** Algae cultivation, synthetic methane, synthetic methanol
- **Enhanced commodity production:** Methanol and urea yield boosting, supercritical CO_2 power cycles
- **Food and drink:** Beverage carbonation, food freezing, chilling and packaging, horticulture
- **Other - industrial applications:** Electronics, metal working, supercritical CO_2

The technologies were assessed according to two parameters - **Market demand (CO_2) and Technology readiness level (TRL)**.

The **market demand** assessment was based on the current (2016) market demand and the estimated 2030 market demand, in the UK and globally ($MtCO_2$/yr). The 2030 demand estimate took into account the anticipated progression of the technologies (in-line with their TRL) and the extent to which the technologies could be realistically deployed over this time period (with consideration of any key barriers).

The **technology readiness level** assessment was based on the current TRL and the time required to reach proven commercial operation (i.e. TRL 9). The timescale to advance to TRL 9 was estimated based on the time required for other industrial technologies to make the same advance in technology readiness.

[2] Note that Enhanced Oil Recovery (EOR) was excluded from the scope of this study.

The outcome of the technology assessment was presented at a stakeholder workshop held at BEIS on 14 October 2016 and further discussed with BEIS. The following seven technologies were selected for detailed assessment.

- **Carbonate mineralisation (Carbonation):** Based on reacting CO_2 with calcium (Ca) or magnesium (Mg) oxide or silicate to form a solid carbonate mineral structure. These materials can be found both in natural form and in waste streams (the focus of this study), such as fly ash from waste-to-energy plants. The carbonates that are produced are stable over long time scales and therefore can be used as construction materials.
- **Concrete curing:** Carbonation using CO_2 to produce solid calcium carbonate ($CaCO_3$) can replace traditional energy intensive steam concrete curing methods. This significantly increases the short-term take-up of CO_2 and offers permanent sequestration of the bound CO_2.
- **Novel cements**: Some researchers and a small number of companies are looking to develop cements which use CO_2 as an ingredient. These cements typically utilise magnesium minerals. The CO_2 is locked in the cement as a solid carbonate.
- **Horticulture:** Industrial CO_2 is used to enrich the growing environment and increase the production yield of crops. The CO_2 stream needs to be very pure to ensure that crops are not damaged. Only a limited portion of the CO_2 is absorbed, and therefore temporarily stored, by the crop (around 80% is vented without uptake in the crop).
- **Polymer production:** Catalytic transformation of CO_2 into polycarbonates, which are then processed further into different types of polymers such as polyurethane. The CO_2 is temporarily stored in the material (up to 50% by weight) for the lifetime of the product.
- **Synthetic methane:** Methane produced through the hydrogenation of CO_2, either through a catalytic or biological process (the former requires a pure CO_2 stream, whereas the latter can utilise a dilute CO_2 stream). The hydrogen (H_2) source is produced through the electrolysis of water. For the methane to be considered a low carbon fuel the process energy would need to be renewable. The CO_2 is temporarily stored in the fuel.
- **Synthetic methanol:** Methanol produced by catalytic hydrogenation of CO_2. The H_2 source is produced through the electrolysis of water (or by-product H_2 can be used). For the methanol to be considered a low carbon fuel the process energy would need to be renewable. The CO_2 is temporarily stored in the fuel.

E.3 Phase 2: Detailed technology assessment

Next, research was undertaken to develop a detailed understanding of the potential of the selected technologies. A stakeholder workshop was held at BEIS on 5 December 2016 to validate draft findings.

Table E.1. overleaf provides a high level summary of key aspects for these technologies. (Please refer to the technology overviews included in chapters 5-11 of the main report for further details).

Table E.1. Summary of key information for the CCU technologies assessed.

Technology	TRL level	UK demand in 2030 ($ktCO_2/yr$)	Location factors and identified regions	Key barriers
Carbonation (via "Accelerated Carbonation Technology")	8	5-43 (excluding soil remediation projects)	o Key factors: availability of waste stream, CO_2 source, market access o Fly ash: co-location with concrete block manufacturers o Steel plants, cement plants, or other historical deposits plants: located at, or near to, the site	o Availability of waste materials o Planning legislation o Long-term track record demanded by construction sector
Concrete curing	7-8	0-100	o Pre-cast concrete: installed at existing concrete plants o Ready-mix concrete: no specific location factors as building sites spread over the country	o Long-term track record demanded by construction sector
Novel cements	3-6	0	o Located near to a port since we are unaware of any significant magnesite deposits in the UK	o Long-term track record demanded by construction sector
Horticulture	9	108-218 (50 supplied via bulk market)	o Reliable source of all-year around CO_2 (and heat) o Possible co-location with waste-to-energy or biomethane plants o Identified suitable areas: East Yorkshire/Hull area, Lea Valley and Thanet	o Limited types of industrial facilities that meet supply and quality requirements o Growers that have recently installed CHP systems are likely to have no (or limited) demand for industrial CO_2
Polymer processing	8	0-100	o Proximity to chemical industry clusters and downstream production processes using the CO_2-based polyols to provide opportunities for industrial symbiosis o Identified suitable areas: Teesside, Grangemouth, Fawley and Hythe	o Lack of plants (even at large pilot scale) producing the polymers in the UK o Risk averseness around new products
Synthetic methane	7-8	0-18	o Access to low cost electricity (for H_2 production), potable water and gas connection that can accept the flow produced o Possible synergies with biomethane injection plants, bio-SNG plants, water treatment plants, fermentation processes	o High costs associated with the synthetic methane process
Synthetic methanol	8	0-145	o Access to low cost electricity (for H_2 production), potable water o By-product H_2 from chlor-alkali production facilities (Runcorn) or coking gas from steel manufacturing (Port Talbot and Rotherham)	o High costs associated with the synthetic methanol process o Restriction on blending levels o Lack of existing methanol fuelling infrastructure

As can be seen from Table E1, the estimated future CO_2 demand from the application of the selected CCU technologies is very modest and limited to around 113-624 ktCO_2/yr by 2030. This is less than 1% of the current CO_2 emissions in the UK. The growth in demand for CO_2 is primarily restricted by the anticipated market demand for CCU products in the UK, suitable locations with sufficient CO_2 at the right quality and access to other raw materials.

E.4 Phase 3: Conclusions and recommendations

Below we have summarised cross-cutting **opportunities** and **barriers** across the selected technologies. These form the basis for identifying the types of support which could advance the development of these CCU technologies and Carbon Capture Utilisation and Storage (CCUS) technology in general, if the support was deemed to be warranted in light of potential contribution to a) the UK's economy and b) climate change mitigation.

- **Goods produced from CCU technologies can serve as a low-carbon alternative to existing products.** By using CO_2 as an input material instead of fossil fuel-based feedstock and/or energy, the CO_2 footprint of the CCU products could be significantly lower provided the process is efficient in its use of other materials and energy, and the other inputs do not place undue carbon burdens on the process. A further potential benefit is the "displacement" effect of using the CCU product instead of the conventional alternative. Of the CCU technologies assessed, carbonate mineralisation offers the greatest carbon abatement potential.
- **Cost acts as a barrier to the uptake of some of the selected CCU technologies.** For example, synthetic methanol is estimated to be at least twice the market price of conventional methanol and synthetic methane is potentially up to five times more expensive than natural gas. The availability of low cost industrial CO_2 is a key limiting factor for its use in horticulture. Efforts need to be directed at reducing the cost of these technologies, for example by improving catalyst performance or lowering the cost of H_2 production via electrolysis. However, some technologies have fundamental limitations which will limit application even if very significant improvements can be made.
- **Some CCU products are reportedly cheaper to produce than their conventional counterpart, but the market is hesitant to widely adopt the products.** CO_2-based polymers may be 15-30% cheaper in the case of polyether polyol production. Similarly, carbonated materials can be produced more cheaply compared to traditional building materials (for example, the cost of Carbon8 aggregate is reportedly up to three times lower than conventional secondary aggregate).
- **The hesitation in the market to use some CCU products is that they *may* have certain perceived disadvantages compared to conventional products or their substitutes.** A key risk is the acceptance of CO_2-based polymers by downstream companies that are purchasing the polymers for use in end-use applications. The acceptability is likely to vary between applications, and this will determine how quickly CCU polymers can be deployed in the market. This is also the case for the carbonation CCU technologies, whose primary customer segment is the construction sector. The construction sector is generally reluctant to adopt new building materials unless they have not been proven for a long period in-situ (15-20 years).
- **Uncertainty in the way to account for and value the CO_2 emission reductions (and potentially the extent of such reductions) from CCU products is limiting the uptake of the technology as an abatement measure.** There is currently limited information on the carbon abatement potential for candidate CCU technologies. In addition, there is no formally agreed life cycle assessment (LCA) methodology with which calculations should be performed. Addressing these aspects is critical if CCU technologies are to be promoted as a carbon mitigation option. Furthermore, the CO_2 emission reductions achieved by utilising and storing the CO_2 in the products are not often not accounted for in many emission reduction policies such as the EU Emissions Trading Scheme (ETS).

- **Despite some potential for CO_2 demand for CCU outside the UK, the market for CO_2 export is likely to be very limited.** The expected CO_2 demand across Europe by 2030 is in the order of 10 times larger than in the UK. Globally, this potential CO_2 demand is about a factor 1,000 lower than the CO_2 produced. It is very difficult to access these markets because the CCU facility should be relatively close to a suitable CO_2 source. The only CO_2 market that the UK might be able target is the European pure/food-grade CO_2 market. This will depend on the development of carbon capture and purification technology in the UK and the market price for the CO_2.
- **Other countries are leading the research and development of many CCU technologies. The UK therefore needs to act quickly if it believes that there will be a significant future market for CCU technologies and economic benefits to the UK.** Many CCU technologies are already being developed outside of the UK. For example, the market leader for synthetic methanol production is Carbon Recycling International, an Icelandic company, while Germany is the market leader for synthetic methane, with several companies deploying this technology. Concrete curing and novel cement technology development is being led by North American organisations, including Carbon Cure and Solidia. The UK has a few projects on industrial CO_2 use in horticulture, whereas the Netherlands is the clear market leader. Notable exceptions include, Carbon8 (a market leader in accelerated carbonation technology), Econic Technologies (CO_2-polymer catalyst development) and ITM Power (supplier of rapid response electrolysers that can be deployed in synthetic fuel production).
- **The CCU technologies can be applied either to industrial clusters or standalone facilities, this is not a key criterion as long as the location criteria are met.** The availability of suitable CO_2 sources in sufficient quantity is a key factor for all CCU technologies, although other factors also apply. The purity of CO_2 and the acceptable distances from CO_2 sources differs per technology.
- **Other benefits may be more important than the CO_2 benefits and can make the business case for the CCU technology.** Synthetic methanol and synthetic methane can be used to provide grid ancillary services by turning excess electricity, which would otherwise be curtailed, into H_2. CO_2-based polymers displace a portion of environmentally polluting (epoxide) feedstocks that are conventially used. Horticulture can potentially utilise industrial CO_2 and heat at more stable competitive prices compared to natural gas and provide a new revenue stream for emitters. Carbonate mineralisation can treat (hazardous) waste streams and turn waste into useful products such as building materials and aggregates instead of the treated waste ending up being landfilled. Concrete curing can take place in less time and (reportedly) reduce cement usage, saving costs.

E.5 Phase 3: Advice on supporting the development of CCU in the UK

It has been shown above that some CCU technologies (in particular mineralisation of wastes) provide potential benefits, but that overall many questions still remain. Prior to detailed policy development, it is therefore recommended that further research is undertaken focussing on long-term climate benefits (i.e. LCA) and an assessment of the techno-economic potential under a range of CO_2 prices.

Potential support measures which would facilitate commercial development of CO_2 utilisation in the UK are detailed below, should it be desired to do so. Government and other stakeholders, including the private sector, could provide such support, with the most urgent need being to fully assess the life cycle emissions of any CCU technologies which are proposed for support.

1. **Raise awareness in CCU products both among private sector parties and the wider public**, for example through:

    - **Detailed LCA for selected CCU processes:** One key finding is that evidence is lacking in a number of areas regarding the life cycle emissions from CCU processes; it is particularly important to conduct consequential LCA based on recognised standards in areas such as accelerated carbonation and novel cements where natural carbonation occurs.
    - **CCU material testing:** Providing support for trials that aim to demonstrate the long-term durability of products used in the construction sector.
    - **Industry/Public awareness:** Further promoting the benefits and business opportunities of CCU in the UK – including to companies, local government and regional/sector organisations. Dissemination of international best practice and case studies, in particular those in the UK.
    - **Product standards and labelling:** The development of product standards and labelling schemes for CCU products would provide confidence to the market and help to stimulate their uptake by the end-consumers.

2. **Providing a financial incentive aimed at accelerating investment in CCU technology development**, for example through:

    - **Demonstration competition:** Government could provide funding for a CCU demonstration competition to help companies bring technologies to market, though any such funding must include a requirement for an independently audited LCA and techno-economic analysis demonstrating scalability of the process prior to large-scale funding (this could sensibly be a stage-gate in the work). Industrial co-funding of a significant share of the cost would demonstrate that companies consider these technologies to be potentially profitable with their internally projected CO_2 price.
    - **Supporting research and development (R&D):** Providing (financial and technical) support to UK R&D in CCU technologies, particularly with a view to de-risking and scaling up promising existing innovations rather than promoting new innovations; the latter is covered well by the investments in fundamental R&D. Innovate UK would be well placed to co-ordinate this. Promising innovations are those that meet three key criteria: 1. a good overall (net negative) carbon balance; 2. are of a material scale; 3. products that have the potential to be (broadly) economically competitive.
    - **Finance:** Work to help de-risk (first-of-a-kind) CCU projects. For example, through providing government guarantees, or providing access to low cost finance.

3. **Strengthening knowledge transfer involving key stakeholders including CO_2 emitters as well as potential users of CCU products**, for example through:

    - **CCU knowledge transfer in existing UK networks**: Stimulating multi-stakeholder discussion of CCU with the aim of accelerating its uptake in the UK and identifying quick wins that can be realised. Relevant stakeholders are the scientific community, industry (including cluster and sector associations), investors, Local Enterprise Partnerships (LEPs) and national government. LEPs and industry cluster associations are seen as key stakeholders in this process as they are best placed to identify opportunities for industrial symbiosis.

- **International:** The UK could play an active role internationally in the field of CCU. This would provide opportunities for international exchange of lessons learned or cooperation. Such a collaboration would also help to showcase UK companies active in CCU. (The Department of International Trade could also facilitate in this respect.)

Any actions taken should align with the aims of the recently published government Green Paper, "Building our Industrial Strategy"[3].

E.6 Next steps

This study has aimed to further the understanding of the potential opportunities for CCU in the UK and increase awareness of CCU technologies and their benefits. We nonetheless, see a need for further research in this area to build on the findings in this study, in particular focussing on the following areas:

- **LCA:** There is a lack of publically available LCA studies on CCU in general, and in particular for some technologies. Furthermore, there is no commonly applied LCA calculation methodology for CCU. The UK could take the lead in this area given its expertise in LCA and in setting internationally recognised carbon accounting standards (e.g. PAS 2050).
- **Techno-economic assessment:** A detailed techno-economic evaluation of technologies would help BEIS to better understand which (type of) CCU technologies offer the best potential and over what timeframe, and to validate claims on technology performance that some technology developers have made, particularly considering the materiality and economic criteria which complement the LCA.
- **CO_2 mapping:** Detailed mapping of CO_2 sources and corresponding quality or purity with potential demand to identify 'concrete' CCU opportunities in terms of nature of process, location and scale.
- **Waste mapping:** A detailed audit of the alkaline waste streams available in the UK (historical, current and projected) will facilitate understanding of the potential CO_2 abatement opportunities using carbonation CCU technologies.

Finally, there is a need to better understand the CCU potential for the multiple other technologies that were not the main focus of this study to avoid having implicitly picked "winners". This will also importantly help to build up a more representative picture of the total potential for CCU in the UK. Consideration of the potential beyond 2030 should also be explored given that some technologies are at an earlier stage of their technical development.

[3] https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/586626/building-our-industrial-strategy-green-paper.pdf

Table of contents

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1 Introduction

1.1 Background of the study

Carbon capture and utilisation (CCU) in general is considered to involve the ***capture*** of carbon dioxide (CO_2) from either a point source (e.g. power station or industrial process), its ***transport*** and its subsequent ***use***. CCU can be applied in a broad range of applications either as part of a biological or chemical conversion process for the fabrication or synthesis of new products (e.g. building products, polymers), or in processes where CO_2 acts a solvent or working fluid in industrial processes.

There is growing interest to understand the potential for CCU to reduce greenhouse gas (GHG) emissions from energy and industrial related sources, and how it may compliment CO_2 capture and storage (CCS). CCU also potentially creates valuable (low carbon) products and provides opportunities for industrial symbiosis. Furthermore, CCU may also provide both a revenue stream for carbon capture projects and reduce the exposure of industry to increasing carbon prices in the future.

There are, however, a number of challenges that make an **accurate assessment of the potential** for CCU difficult; some of these include:

1. The available evidence on the commercial potential for CCU is limited.
2. Many CCU technologies are at an early stage of development and not yet ready for commercial deployment.
3. There is a lack of robust quantitative data on potential CO_2 markets in the UK, specifically in terms of sectors and geographical location.
4. There is a lack of market research into the “green premium” that consumers would be prepared to pay for CCU products.
5. Many technologies and/or products capture CO_2 for only a short time before re-releasing it.

1.2 Objectives

In September 2016, the UK Department for Business, Energy and Industrial Strategy (BEIS) commissioned Ecofys and Imperial College London to assess the potential of CCU in the UK to 2030. The key objectives of this study were to:

- Examine and report on the potential of CCU in the UK to help long-term CO_2 abatement.
- Identify the most promising applications of CCU in the UK - including an assessment of the Technology Readiness Level (TRL), carbon abatement potential, most promising deployment locations and barriers that may hinder development.
- Advise on innovation support.

This report presents the findings of this study, and is structured as follows:

- Chapter 2 summarises the methodology and approach taken to achieve the objectives of this study.
- Chapter 3 provides an initial evidence review of CCU technologies.
- Chapter 4 provides an overview of the carbon abatement potential of CCU technologies.
- The seven subsequent chapters contain the detailed findings for the most promising applications of CCU in the UK. The technologies are presented in this order:
    - Chapter 5 - carbonation (carbonate mineralisation)
    - Chapters 6 and 7 - concrete curing and novel cements
    - Chapter 8 - horticulture
    - Chapter 9 - polymer processing
    - Chapter 10 - synthetic methane
    - Chapter 11 - synthetic methanol
- The conclusions of this study are presented in Chapter 12.
- Recommendations on innovation support and next steps are provided in Chapter 13.

2 Methodology and approach

2.1 Overall approach

The approach taken in this study is summarised in Figure 1. The first phase consisted of a literature review to build a long list of CCU technologies for consideration and to gather information with which to prioritise these technologies (focussing on the TRL and market demand). A stakeholder workshop was held on 14 October 2016 to discuss the most promising CCU technologies for analysis in the next phase.

Next, extensive research was undertaken to develop a detailed understanding of the potential of these selected technologies (refer to section 2.3 for further details). The topics addressed in this detailed technology research included key features of the technology, applicability, status quo, current technology status, future growth potential to 2030, locations for deployment in the UK, benefits and opportunities and barriers and required support. Information obtained from literature was complemented by interviews and data provided by stakeholders. In addition, a stakeholder workshop was held on 5 December 2016 to validate the draft findings.

The final phase of the project developed the recommendations and conclusions of this study. This was performed by synthesising the findings of the work performed in Phase 2 and discussion with industry stakeholders.

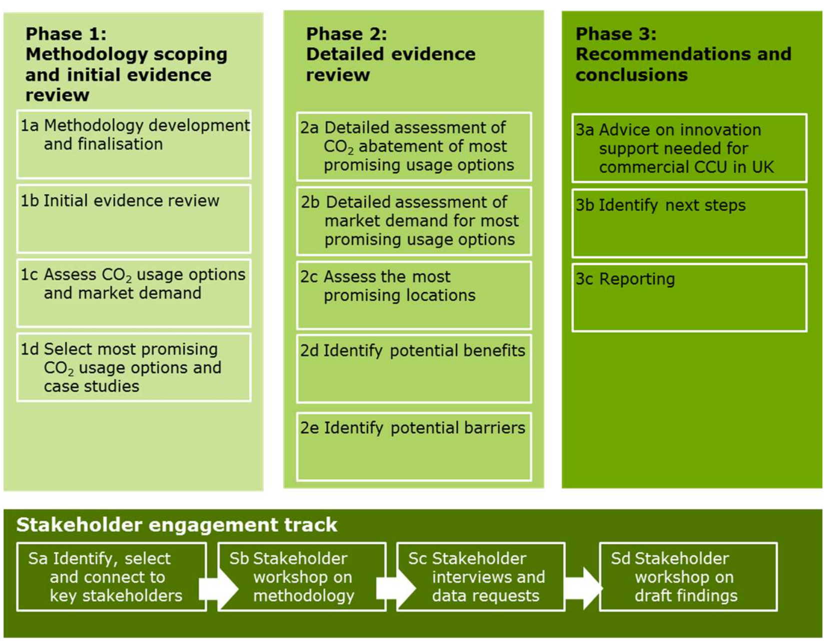

Figure 1. Study approach.

2.2 Phase 1

2.2.1 Developing an overview of CCU technologies and selection of the most promising technologies for further investigation

The overall aim of Phase 1 was to identify the most promising CCU technologies in the context of UK deployment to 2030. An initial list of CCU technologies to be considered was available from earlier work Ecofys performed for DECC in 2016 on the topic of opportunities for CO_2 utilisation in the UK[4]. A literature review was undertaken to identify whether any additional CCU technologies should be considered.

2.2.2 Scoring criteria

The CCU technologies were assessed according to scoring criteria that took into account a high level estimate of the **market demand** and **technology readiness level (TRL)**. Each technology was assigned a market demand score and a technology readiness score.

The **market demand score** for CO_2 was based on the estimated *current (2016)* and *2030 market demand*, in the UK and globally ($MtCO_2$/yr). The market demand was determined through a literature review, complimented with targeted stakeholder engagement. Literature sources that were assessed included publically available reports that provide estimates for the CCU demand (either at a UK or global level[5]), CCU technology specific literature, information included on company websites, as well as information sources that provide data on the size of the relevant sector or target market for the CCU technology. Sector organisations and other relevant stakeholders[6] were contacted to provide market data, as well to identify companies that are current CO_2 users along with their CO_2 demand. Views on the potential CO_2 demand in 2030 for the CCU technologies were also requested.

The 2030 demand estimate took into account the anticipated growth rate of the market in which the technology would be deployed, the progression of the technologies (in-line with their TRL) and the extent to which the technologies could be realistically deployed over this time period with consideration to any key barriers. The estimates for potential future UK demand included an appreciation of the extent to which technology deployment may be restricted to certain geographic locations, or linked to particular existing clusters of industrial activity.

The scoring approach that was applied to assess the UK and global market demand is summarised in Table 1. It should be stressed that the estimates made reflect "order of magnitude" estimates, and represent the *anticipated* demand range that a technology is likely to fall under, rather than an exact estimate of demand. This is particularly relevant for the period 2030 given the large uncertainty that exists in providing such an estimate.

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[4] Ecofys, Opportunities for CO_2 utilisation in the UK, Final report, May 2016. Unpublished.

[5] Key literature sources include: (Element Energy, 2014) – relevant for the UK demand and (GCCSI, 2011) and (CO_2 Sciences and Global CO_2 Initiative, 2016) – relevant for the global demand.

[6] Other stakeholders contacted included CO_2 suppliers, companies developing CCU technologies and companies that could deploy CCU technologies.

The **market demand score** for each technology was calculated as follows:

= [**UK** (2016 score x 20% + 2030 score x 80%) x3[7]] + [**Global** (2016 score x 20% + 2030 score x 80%)]

Table 1. UK and Global market demand scoring.

Category	$MtCO_2$/yr demand	Score
UK demand		
None	0	0
Very low	<0.009	0.5
Low	0.01-0.49	1
Medium	0.5-0.99	2
High	>0.10	3
Note: An uplift of x3 was applied to the UK scores.		
Global demand		
None	0	0
Very low	<1	0.5
Low	1-5	1
Medium	5-9	2
High	>10	3

The **technology readiness score** was based on the current TRL and the estimated time required to reach proven commercial operation (i.e. TRL 9). The TRL assessment built on an earlier evaluation of TRL levels by Ecofys for the Department of Energy and Climate Change (DECC) for a range of CCU technologies; this assessment was updated using the latest literature, complimented with information provided by industry stakeholders. The timescale to advance to TRL 9 was assessed by considering the time required for other industrial technologies to advance from the CCU technology's current TRL level to TRL 9.

As a starting point, it was assumed that technologies advance on average at rate of 2 TRLs per decade based on historical analogies of the timespans that were required to reach TRL 9 in other sectors[8]. This was informed by Imperial College London's previous work in other projects where expert opinion had been sought from on the rates of progression possible in other technologies (for example novel CCS technologies). The estimates were then sense checked, with consideration to the specific merits and hurdles of each technology.

The scoring approach applied to assess the technology readiness is summarised in Table 2 overleaf.

[7] The UK component of the demand score was multiplied by a factor of 3 to weight the score towards technologies that are considered to be more promising for the UK.

[8] Based on analysis undertaken by Imperial College London.

Table 2. TRL descriptions[9] and scoring.

Current TRL	Score
1 Basic research	1
2 Applied research	2
3 Critical Function or Proof of Concept Established	3
4 Laboratory Testing/Validation of Component(s)/Process(es)	4
5 Laboratory Testing of Integrated/Semi-Integrated System	5
6 Prototype System Verified	6
7 Integrated Pilot System Demonstrated	7
8 System Incorporated in Commercial Design	8
9 System Proven and Ready for Full Commercial Deployment	9
Timeframe to reach TRL 9	**Score**
<2016	5
2016-2019	4
2020-2025	3
2026-2030	2
>2030	1

The **technology readiness score** for each technology was calculated as follows:

= Current TRL score + Timeframe to reach TRL 9 score

The technology readiness and market demand scores were then assessed to enable selection of the most promising technologies. The outcome of this exercise is included in chapter 3. The results from these analyses were validated at a stakeholder workshop held on 14 October 2016. More information on the outcomes of this workshop are presented in section 3.2.

2.3 Phase 2

The selected technologies were then subjected to a detailed assessment, building on the initial evidence gathered in Phase 1 (see section 3.3). This involved extensive stakeholder engagement and identification of additional literature sources. Draft final results were presented at a second stakeholder workshop held on 5 December 2016.

To ensure that a consistent approach was taken between the technologies, the assessment focussed on the following aspects.

- **Technology outline and features:** A description of the main features of the technology option, including a basic overview of the process (e.g. energy and material inputs required).
- **Market application:** Assessment of the specific sectors and applications that the technology is, or could, be deployed in.
- **Status quo:** Overview of the current situation regarding the technology and product or production process the technology is supposed to replace. A brief analysis of why this may not be occurring.
- **Current technology status:** Assessment of the current (2016) technological status of the option (TRL level), its level of deployment and the associated CO_2 demand. Information on any research efforts to advance the technology.

[9] https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/563830/Phase_5_EEF_Guidance_notes.pdf (See Appendix 2 - Technology Readiness Levels (TRLs))

- **Future growth potential to 2030:** Assessment of the potential deployment of the technology in 2030 and the associated CO_2 demand. Consideration of whether there is potential to export the CCU technology abroad.
- **Locations for deployment:** Analysis of the key criteria for deployment of the technology in the UK, with a view on the most promising geographical locations. Consideration as to whether the technology is more suited to clusters or standalone plants was given.
- **Benefits and opportunities:** Assessment of any additional opportunities of incentivising the deployment of the technology. This included an assessment of if/how the deployment could benefit carbon capture technology and CCUS projects.
- **Barriers and required support:** Identification of the key barriers the technology faces to be able to be deployed in practice. Recommendation on the possible forms of support that could assist in addressing these barriers help to advance technology deployment if desired.

The detailed technology assessments are presented in chapters 5-11 of this report.

3 Evidence review of CCU technologies

3.1 Overview of long list of CCU technologies

In Phase 1 a long list of CCU technologies was identified and assessed in terms of market demand for CO_2 and technology readiness. The key results are summarised in Appendix 1.

These technologies were categorised as follows[11]:

- **Chemicals production:** CO_2 can be used in the synthesis of a range of intermediates for use in chemical and pharmaceuticals production. Conversion methods require the use of catalysts, heat and/or pressure to break the stable CO_2 structure, and include photocatalysis or electrochemical reduction. One of the most promising technologies is the use of CO_2 to make various polymers, such as polycarbonates.
- **CO_2 mineralisation:** This group of technologies relies on the accelerated chemical weathering of calcium (Ca) or magnesium (Mg) based minerals using CO_2, which can be found in natural form and in waste streams. It can be used in a range of applications, typically involving the production of construction materials (e.g. concrete curing or novel cements) or in more niche circumstances such as mine tailing stabilisation.
- **CO_2 to fuels carrier:** Within this group, technologies which can provide a means for new types of energy vectors are covered. They partly consist of commercially established technologies linked to more novel use (e.g. synthetic methanol), and more embryonic forms of energy carrier development (e.g. biofuels from algae).
- **Enhanced commodity production:** This group of technologies involve using CO_2 to boost production of certain products, typically where CO_2 is already used but could be modified (e.g. urea or methanol yield boosting). It also includes using CO_2 as a substitute in existing technologies (e.g. for steam in power cycles). These technologies generally involve applying new methods to techniques which are in commercial practice today, but could be modified to use CO_2. (Note that CO_2 use in enhanced oil recovery is not within the scope of this study.)
- **Food and drink:** High purity (food or beverage grade) CO_2 is currently used for beverage carbonation, in food freezing, chilling and packaging and in horticulture to enhance the production of crops.
- **Other - industrial applications:** Industrial grade CO_2 is currently used in a wide range of applications, including in electronics, metal working, as a refrigerant gas and in water treatment and pH control. Supercritical CO_2 is also used in coffee decaffeination, extraction of aromas or flavours and plant substances, pharmaceutical processes and as a solvent in dry cleaning. Other uses of CO_2 include fire suppression and as "dry ice".

[11] Based on (Ecofys & Carbon Counts, 2013).

3.2 Outcome of the first stakeholder workshop

The workshop held on 14 October 2016 was attended by 15 industry stakeholders, along with representatives from BEIS (see Annex 2 for a list of participants). The main aims of the workshop were to:

- Understand the participant's views on CCU
- Identify and prioritise barriers and drivers for CCU deployment in the UK
- Validate the technology scoring methodology
- Identify locations for CCU deployment in the UK
- Discuss the carbon abatement effect of CCU technologies (summarised in chapter 4)

In addition, a selection of UK and international CCU case studies were presented and discussed, namely:

- **British Sugar-Cornerways (UK):** Horticulture
- **Carbon8 (UK):** Carbonate mineralisation
- **Carbon Cycle (UK):** Carbonate mineralisation
- **Carbon Recycling International (Iceland):** Synthetic methanol
- **Covestro (Germany):** Polymer processing

3.2.1 Views on CCU

The workshop participants viewed CCU as a technology that could be used to decouple CO_2 emissions from economic growth. To realise this benefit, it was indicated that a market first needs to develop for the CCU industry, and furthermore that (dis)incentives to stimulate customer demand will be required to develop this market. The development of the CCU industry will require a CO_2 price, but at the same time, it was recognised that the CCU industry could also be a CO_2 price setter.

The workshop participants agreed that CO_2 utilisation could be an abatement solution for small CO_2 emissions sources, but that it does not replace the need for CO_2 abatement. In this regard, the most attractive CCU technologies offer long-term storage, which can be considered to be equivalent to emissions abatement. It was also recognised that it is important to have a holistic understanding of how CCU technologies reduce GHG emissions. As such, it was argued that detailed life cycle assessments of the technologies are needed.

The workshop participants saw CCU as a complimentary technology to CCS, as the development of CCU technology provides a potentially low-cost opportunity to enhance carbon capture technology. CCU can potentially remove the need to transport captured CO_2 to a storage location. Participants, furthermore, stated that in certain cases CCU might be cheaper than CCS to implement.

3.2.2 Barriers and drivers for CCU deployment in the UK

The following ***barriers*** for CCU were identified by stakeholder participants, with those highlighted in bold being viewed as the key barriers:

- **Integration of CCU technologies within existing industrial processes**
- **First-of-a-kind-plant risk**
- **Regulatory uncertainty**

- **Lack of funding/support for scale-up**
- **CCU "not seen" by itself next to CCS (stakeholder views vs. government policy and regulation)**
- **High capital and operating costs per tonne of CO_2 used**
- Competition with existing market products
- Competition between CCU technologies
- High energy (or input) requirements
- Long technology lead-time (of up to 10 years)
- CO_2 emitters are not looking at CCU
- Mismatch of scale between CO_2 emitters and users
- No "push" (CO_2 price) or "pull" for CCU (no current value in low carbon products)
- Planning regulations
- Waste disposal regulations
- Storage certainty

Regulation was seen by some stakeholders as a way to increase the deployment of CCU. However, others considered that over reliance on regulation introduces regulatory risk. Specifically, if the regulation changes then the market for the product may disappear, or the business case for the CCU technology may weaken.

The following ***drivers*** for CCU were identified by stakeholder participants, with those highlighted in bold being viewed as the key drivers:

- **Creating opportunities for (new) revenue streams**
- **Supporting industrial innovation**
- **Decarbonising industrial growth**
- **Presence of suitable regulatory and policy frameworks**
- **Supporting CCS technology development**
- Consumer preference for low carbon products and services
- Successful demonstration of CCU technologies
- Reduction of GHG emissions
- Circular economy (conceptually/funding)

3.2.3 Technology scoring methodology

The approach taken for the CCU technology assessment (as described in section 2.2.2) was discussed and the workshop participants were asked to provide feedback and initial results. Overall, it was considered that the proposed approach was a reasonable basis with which to assess the technologies. One key recommendation, however, was to split mineralisation of wastes from mineralisation of rocks extracted for this purpose (carbonate mineralisation was considered to be too broad a category).

3.2.4 Locations for CCU deployment

The workshop participants were split into two groups and asked to brainstorm on the question "*where will CCU develop first?"*, taking into account the following three considerations:

- Location
- CO_2 supplying / consuming industry
- Clusters vs. stand-alone situation

The groups indicated that "CCU is already here in the UK", although it was also acknowledged that the number of projects is currently limited. These projects include Carbon8's two operational plants located at Brandon and Avonmouth, as well as examples of CCU in horticulture, such as British Sugar-Cornerways. CCU is also widely applied in the food and drink sector, primarily in beverage carbonation, and to a lesser extent in food freezing, chilling and packing applications. Tata Chemical Europe's sodium bicarbonate plant at Winnington has also been a major CO_2 offtaker in recent years following the closure of Tata's soda ash plant that had been previously supplied the CO_2. It is estimated that the total size of the UK market in 2016 was in the range of 400-500 ktCO_2/yr.

The majority of these current CCU projects are located as standalone plants, rather than in major industrial clusters. In the case of Carbon8, the plants are co-located next to concrete block manufacturers, rather than to either the source of CO_2 or waste raw material which are both transported to the plant by truck. The main consideration for Carbon8 is to locate its production close to market (concrete block manufacturers) to minimise transport distance and cost. The Cornerways nursery is located at a distance of just 500 m from British Sugar's Wissington sugar beet refinery, from where the CO_2 (and heat) is sourced. For further details of these projects, see Appendix 3.

Bulk CO_2 is available through an established network of suppliers (Air Liquide, Air Products, BOC/Linde and Praxair) and quality grades, namely: "industrial grade" (used in refrigeration, fire extinguishing and industrial applications, "food grade" (used to freeze, chill or pack food products) and "beverage grade" (used as an ingredient in products sold for human consumption). Each of these grades have to conform to specific industry standards[12], although the exact specifications can vary between suppliers depending on the sources of their CO_2 and target markets. As a general rule, industrial grade CO_2 has a purity of >99%, while food/beverage grade CO_2 has a purity of >99.98% with stricter limits on trace impurities compared to industrial grade.

In the UK, CO_2 is sourced from a limited number of industrial plants. These include two ammonia plants at Billingham (Teeside) and Ince (Chester) which are both operated by Canada Fertiliser (CF), bioethanol plants (e.g. Ensus in Teesside[13]), distilleries (e.g. North British Distillery in West Lothian, Scotland[14]) and other fermentation plants (e.g. Cargill in Greater Manchester[15]) and more recently from crop based biomethane upgrading plants. It was indicated that the UK CO_2 market has been short in recent years, particularly when the Ensus plant has been closed, requiring CO_2 to be imported from northern Europe (France and the Netherlands) to meet demand[16].

As part of the brainstorm the participants were also asked to indicate the locations on a map of the UK. Both groups proposed broadly similar locations, namely the main industry clusters in the UK (e.g. Grangemouth, Humberside, Merseyside, Neath and Port Talbot and Teesside). In addition, the Scotland/North England border was identified as a potential area for the deployment of those CCU technologies whose business case is reliant on the use of curtailed electricity (due to the restriction in capacity of the B6 interconnector between England and Scotland). Finally, South Wales and South west England were cited as having limited CCS potential due to the lack of geological storage, which may serve to benefit CCU.

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[12] Industrial grade: BS 4105 (type 2) and BS 6535; Food grade: EIGA (European Industrial Gas Association) Grade for Food & Beverage; Beverage grade: Further conforms to the ISBT standard and FSSC 22000 standard in manufacturing. Often, beverage manufacturers have further quality control requirements for suppliers of CO_2.

[13] http://www.ensus.co.uk/Pdf/Company/About_us.pdf

[14] http://northbritish.co.uk/products/co-products/co2-recovery/

[15] http://www.boconline.co.uk/en/news-and-media/press_releases/news2015-11-19.html

[16] CO_2 is imported into Teesside and Purfleet (near London).

However, an interesting insight from one group was that presenting locations on a map is an "over simplification" as CCU is business-case dependent. This was illustrated by the group broadly agreeing with both of the following statements: "*CCU will start in clusters with high CO_2 emissions*" and "*CCU will start in locations with just small CO_2 emissions*".

A take-home from this was that a first step it was more appropriate to focus on CCU deployment "location factors". A selection of the key factors proposed by the participants are included below:

- Access to a low cost source of CO_2 at the desired quality.
- Synergies that enable connecting additional CO_2 sources or users.
- CO_2 cost impact (CCU will develop where CO_2 cost is highest).
- Availability of excess renewable electricity/ curtailment.
- Clusters without CCS potential.
- Chemical process clusters (as they have the knowledge and expertise).
- Co-location vs. distance of CO_2 source and CO_2 user (depends on the CCU application).
- Co-location with existing product manufacturers.

3.3 Selection of technologies for further assessment

The technologies that were prioritised for further detailed assessment are detailed below, following discussion with BEIS. It should be noted that Concrete curing and Carbonate mineralisation was supplemented by the additional category, Novel cements, during the course of Phase 2.

- **Carbonate mineralisation (Carbonation):** Carbonation technology is based on reacting CO_2 with calcium (Ca) or magnesium (Mg) oxide or silicate to form a solid carbonate mineral structure. These materials can be found both in natural form and in waste streams (the focus of this study). Waste streams include fly ash from combustion, slag from steel production and wastes from cement production. Mineral carbonation occurs naturally, but is a very slow process, and therefore needs to be accelerated considerably in order to be a viable method of capturing and reusing CO_2 from anthropogenic sources.
- **Concrete curing:** Concrete curing in general refers to the hydration process of various elements within the cement that is part of the concrete mix. Alternatively, it is proposed that carbonation can take the place of hydration during the curing phase, to produce solid calcium carbonate ($CaCO_3$). This significantly increases the short-term take-up of CO_2 and offers permanent sequestration of the bound CO_2.
- **Novel cements:** Though ordinary Portland cement is used in the overwhelming majority of cement applications, there are other types of cement available, including cements which use CO_2 as an ingredient. The CO_2 is locked in the cement as a solid carbonate. The mineralisation of CO_2 within the novel cements is typically associated with the primary bonding reaction that generates the strength of the cement, in many cases utilising Mg minerals.
- **Horticulture:** Use of industrial CO_2 to enrich the growing environment and increase the production yield of crops. Heat is also added to extend the growing season. The CO_2 used in horticulture needs to be very pure to ensure that crops are not damaged.
- **Polymer processing:** Transforming CO_2 into polycarbonates using catalysts, which are then processed further into different types of polymers such as polyurethane.

- **Synthetic methane:** Methane produced by catalytic or biological hydrogenation of CO_2 (the former requires a pure CO_2 stream, whereas the latter can utilise a dilute CO_2 stream). The H_2 is produced through the electrolysis of water. For the methane to be considered a low carbon fuel then the process energy would need to be renewable.
- **Synthetic methanol:** Methanol produced by catalytic hydrogenation of CO_2. The H_2 is produced through the electrolysis of water, or by-product H_2 can be used. The minimum CO_2 quality is 99% purity at the inlet to the reactor. For the methanol to be considered a low carbon fuel then the process energy would need to be renewable.

4 Carbon abatement potential of CCU

There are several key aspects that should be considered when assessing the carbon abatement potential of CCU, including:

- The ability to capture and effectively store CO_2 for shorter or longer periods through creating a new product or displacing existing production method by a new process that uses CO_2.
- The displacement of fossil fuel combustion as a source of CO_2 for industrial processes.
- The change in energy efficiency of some processes/energy intensity of some products.
- The product and process lifecycles associated with the CCU technologies.

Following the capture of CO_2, the duration of CO_2 binding prior to its release into the atmosphere can be classified as weeks, months, years and long-term (e.g. over 50 or 100 years). The latter situation can be considered to be the only one which effectively contributes to GHG emissions mitigation.

In the first stakeholder workshop, participants argued that 50 years should not be considered a long-loterm duration, when compared to CCS, which is permanent. Participants therefore recommended that a new category that classifies so-called "real" permanence should be added. In addition, participants also suggested that the timeframe for permanence should be legally defined as the CCU market will entail monetary exchanges[17]. Opinion was divided on the shorter timeframes (weeks and months), with some participants indicating that such short timeframes are meaningless. On the other hand, other participants suggested that storage and displacement effects should be considered together, as the overall impact of short-timeframe CCU applications, e.g. use of CO_2 in horticulture, may still be beneficial to GHG abatement if the displacement effect is large.

While CCU has the potential to reduce GHG emissions, this is not necessarily always the case. This, for example, depends on the energy efficiency of the capture and conversion processes. The CO_2 emissions resulting from the use of fossil fuel energy (including electricity) or chemicals used in the capture and conversion processes, could potentially counterbalance the emissions avoided by the CO_2 capture. Therefore, it is key to assess whether a specific CCU process is more favourable compared to the conventional alternative (von der Assen et al., 2013; Von der Assen et al., 2014). Life cycle assessment (LCA) is a suitable tool for determining the carbon abatement of CCU technologies. In LCA the environmental impacts of a product or process are assessed taking into account the entire life cycle from cradle to grave (see Figure 2 below).

[17] The Lowest Cost decarbonisation for the UK: The critical role of CCS report published by Parliamentary Advisory Group on CCS published in September 2016 (Oxborough report) states that, *"The CCS Certificate System will certify safe, long-term storage of CO_2 by any means, not just geological storage."* (see para 340) This implies that permanent storage options, such as mineral carbonation will also count, but non-permanent options (such as CO_2 to fuels or plastics) will not count.

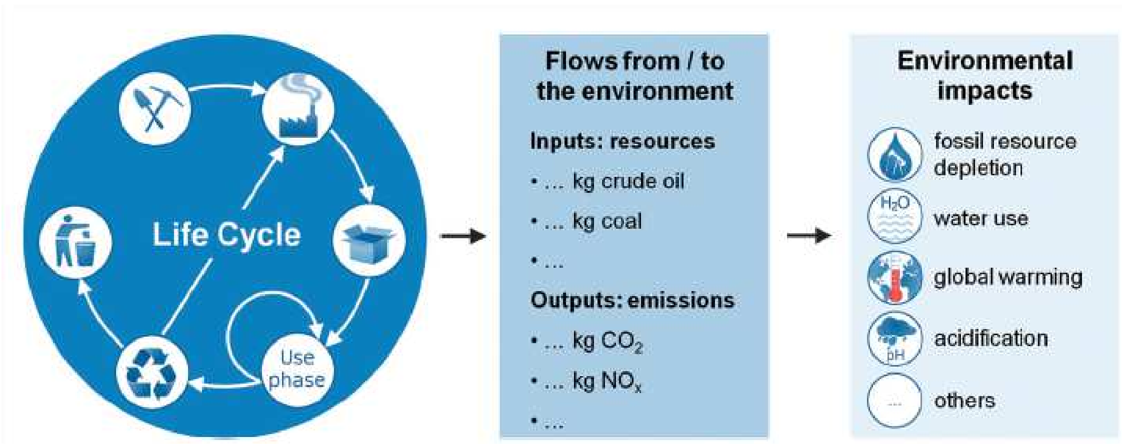

Figure 2. General concept of LCA (Source: von der Assen et al., 2014).

While LCA can be a valuable tool for assessing CCU technologies, there are some specific points of attention in the context of CCU. In addition, no specific guidelines for LCA of CCU technologies currently exist.

- **Taking the supply chain into account:** When assessing a CCU system, the utilised CO_2 could be intuitively treated as negative emissions if the CO_2 is obtained from either a biogenic source or captured directly from the atmosphere. However, this assumption does not take into account the upstream emissions of the CO_2 capture process (e.g. caused by the energy requirement of the capture process itself). Therefore, the production process of the feedstock CO_2 has to be taken into account when assessing the carbon abatement of a CCU application (Von der Assen, 2013).
- **Creating a fair comparison:** To be able to draw meaningful conclusions it is important to create a fair comparison. The CCU system should be compared to an equivalent non-CCU system producing the same outputs (functional unit). This requires an astute choice of system boundaries for both the CCU and non-CCU system. When looking at the CCU system in isolation, it is not possible to assess whether the system is in fact more favourable from an emissions point of view compared to the conventional alternative. For example, Edge environment (2011) reports LCA results for various CCU technologies in terms of life cycle CO_2 equivalent emissions per tCO_2 stored. However, since these are not compared to their non-CCU conventional alternatives, it is not possible to draw a conclusion regarding the environmental favourability of the CCU options. The temporal scope is also an important factor to consider when selecting the solutions to compare. The existing LCA studies on CCU often compare novel, immature technologies with current reference technologies. However, for a fair comparison the CCU system should be compared with a scenario representing likely conditions at the time when the technology is expected to be market ready (Bennet et al., 2014). As a result, the climate benefits of CCU technologies might often be overestimated.

- **Allocation of emissions:** A complete CCU system includes the point source (e.g. power plant) from which the CO_2 is captured as well as the process in which the captured CO_2 is utilised. The CCU system thus delivers two products: the main product of the point source (e.g. electricity) and the final product for which the captured CO_2 is used. In many cases, two different companies are involved in the capture and utilisation processes and both will be interested in the emission reduction credits of the CCU technology. For a product-specific LCA the emissions of the entire CCU system have to be allocated to the individual products. The commonly used ISO 14044 standard for LCA includes a hierarchy of allocation methods. The preferred option is the use of the system expansion approach for processes with multiple outputs. Using this approach, all functions of a system are considered jointly using one functional unit (e.g. the production of a certain amount of product and a certain amount of electricity). The approach allows for a fair comparison between CCU and non-CCU options, avoiding ambiguous choices regarding allocation methods, such as allocation by economic value or energy content (von der Assen et al., 2013). Although not resulting in product-specific results, the system expansion approach is most suitable for assessing the environmental sustainability of CCU options, compared to their non-CCU alternatives.
- **Accounting for delayed emissions:** Most CCU processes only temporarily store CO_2 in products, e.g. for a period shorter than 100 years. This is too short a duration to meaningfully mitigate climate change. However, in traditional LCA practice the emission's point in time during the life cycle of a product is not reflected. Whilst, alternative time-corrected characterisation factors have been developed to account for delayed emissions (von der Assen et al., 2013), both the commonly used ISO 14067 standard for the Carbon Footprint of Products and Greenhouse Gas Protocol Standards do not allow for taking into account the effect of delayed emissions, although the impact of delayed emissions may be reported separately from the carbon footprint (ISO 14067:2013; GHG Protocol, 2013). In contrast, the PAS 2050 standard specifies that carbon not emitted within the 100 year assessment period shall be treated as stored carbon. Regarding delayed emissions within the 100 year timespan, PAS 2050 also only allows for reporting results separately from the mandatory single-release assessment). According to current standards, temporary carbon storage should only be reported separately from the carbon footprint results.
- **Data availability:** LCA is data driven and the quality of the results ultimately depend on the quality of the input data. Given that many CCU technologies are in early stages of development, the data availability is currently poor.

Given the very limited data availability for CCU technologies, it has not been feasible to perform LCAs the context of this study. Instead, we aim to summarise the key findings available from LCAs in other studies and highlight the main parameters and uncertainties influencing the global warming impact of the CCU technologies. While a full LCA takes into account multiple impact categories (e.g. fossil resource depletion, acidification, water depletion), we only focus on global warming impact in this study.

We also comment on the overall carbon abatement effectiveness of each of the CCU technologies from the perspective of the duration of CO_2 storage and other abatement effects, such as the displacement of fossil fuels.

4.1 Carbonation

Summary of carbon abatement effectiveness indicators

- **Efficiency of CO_2 absorption:** The CO_2 is absorbed and locked in minerals. A high percentage of the CO_2 fed can be stored.
- **Duration of storage:** Permanent.
- **Other abatement effects:** Displacement of other aggregate materials currently in use, including the associated life cycle emissions.
- **Energy input and intensity of processing:** Depends on the specific carbonation process.
- **Input materials:** Waste material. Various options, depending on the type of material produced.

Summary of literature

No publically available LCA studies focusing on carbonation were identified.

According to Carbon8[18], its aggregate is carbon negative ("more CO_2 is permanently captured during the process than used in its manufacture"). On average, the carbon performance is reported as 40 kgCO_2/t aggregate, although this depends on specific absorption rate of material. Carbon8 also state that for every tonne of their aggregate used 1.4 tonnes of natural aggregate is saved. The basis for these claims, however, are not reported and could therefore not be verified.

4.2 Concrete curing

Summary of carbon abatement effectiveness indicators

- **Efficiency of CO_2 absorption:** The CO_2 reacts with parts of the concrete. Of the CO_2 injected or fed to the curing environment only a part will be absorbed. Over the life time of concrete additional CO_2 will be absorbed, as is also the case with regular concrete. Depending on the initial saturation rate and the permeability, this may be either a higher or lower continuing absorption rate.
- **Duration of storage:** Permanent.
- **Other abatement effects:** Some claims that greater strength of bonding could result in a lowering of cement content (up to 10%) and the associated emissions.
- **Energy input and intensity of processing:** Limited to energy required for capturing, transportation and conditioning of CO_2. This may be substantial, however, in particular if CO_2 is transported to building sites by truck.
- **Input materials:** None.

Summary of literature

No publically available LCA studies focusing on concrete curing were identified.

Carbon Sense Solutions (renamed Carbon Cure in 2011) report that GHG emissions can be reduced by about 80% through reducing the CO_2 released from steam curing and by permanently sequestering CO_2 within the concrete[19]. The process also reportedly uses 38% less energy than the conventional curing process. The basis for these claims, however, are not reported and could therefore not be verified.

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[18] http://c8a.co.uk/our-aggregate/

[19] https://www.novascotia.ca/nse/cleantech/docs/CarbonSense.pdf

4.3 Novel cements

Summary of carbon abatement effectiveness indicators

- **Efficiency of CO_2 absorption:** The CO_2 reacts with other materials to form the cement. Of the CO_2 injected or fed to the curing environment only a part will be absorbed. Over the lifetime of concrete some more CO_2 will be absorbed at a diminishing rate. This also happens with regular concrete, however, depending on the type of novel cement, the rate of curing and the rate of CO_2 penetration, this long-term absorption may be either higher or lower than regular concrete.
- **Duration of storage:** Permanent.
- **Other abatement effects:** Substitution of regular cement.
- **Energy input and intensity of processing:** Depends on the process required for producing the novel cement.
- **Input materials:** Raw materials or waste products, depending on the type of cement.

Summary of literature

No publically available LCA studies focusing on novel cements were identified.

Solidia assert that their process can reduce carbon emissions by up to 70% (Solidia Technologies, 2016). The basis for this claim, however, is not reported and could therefore not be verified.

4.4 Horticulture

Summary of carbon abatement effectiveness indicators

- **Efficiency of CO_2 absorption:** A portion of the supplied CO_2 will be absorbed.
- **Duration of storage:** The use of CO_2 in horticulture is short-lived (days). A portion of the CO_2 that is added to the glasshouse will be absorbed by the crop, and typically fixed for a few days until digested. In addition, CO_2 will also be vented from the glasshouse once the CO_2 level reaches around 1,000 ppm, or for the purpose of humidity control – without any benefit to the crop. (This is the same in the present situation.)
- **Other abatement effects:** The use of industrial CO_2 (and heat) typically displaces the use of natural gas fired CHP or boilers. However, to realise abatement these avoided emissions need to outweigh the emissions related to processing and transportation.
- **Energy input and intensity of processing:** Limited to energy required for capturing, transportation and conditioning of CO_2. This may be substantial, however, in particular if CO_2 is transported to glasshouses by truck.
- **Input materials:** None.

Summary of literature

The utilisation of captured CO_2 in horticulture has the potential to avoid significant amounts of CO_2 emissions, primarily through avoided natural gas use. Potential bottlenecks are the purity of the CO_2 as horticulture is limited to very pure sources of CO_2 (otherwise the CO_2 source needs to undergo purification with associated energy use) and the transport distance. There must be a right balance between the avoided gas use at the greenhouse and the energy use for compression and transport of the CO_2. If a connection is made between an industrial plant with almost pure CO_2 and a nearby greenhouse, emissions reductions by both the industry and the greenhouse are possible (Vermeulen, 2014).

4.5 Polymer processing

Summary of carbon abatement effectiveness indicators

- **Efficiency of CO_2 absorption:** The CO_2 is temporarily stored in the material as a part of the polymer itself.
- **Duration of storage:** Lifetime of the material (years).
- **Other abatement effects:** Emissions savings due to the replacement of feedstocks such as propylene oxide (PO) and ethylene oxide (EO) – termed epoxides.
- **Energy input and intensity of processing:** Low.
- **Input materials:** Epoxides – PO and EO.

Summary of literature

Von der Assen & Bardow (2014) performed an LCA of CO_2-based polyethercarbonate polyols in a real industrial plant. CO_2 capture from a lignite power plant equipped with a pilot plant for CO_2 capture is considered. Transport of the captured CO_2 over a distance of 40 km is included. The study uses the system expansion approach and the functional unit is the production of 1 kg polyols for polyurethane production combined with the supply of 0.36 kWh electricity to the German electricity grid (i.e. the power plant is the point source used to capture the CO_2 used in polyol production).

For a CCU system with polyethercarbonate polyols containing 20% by weight CO_2, the study finds that by using feedstock CO_2 for polyol production, the system wide GHG emissions can be reduced by 14–19% compared to conventional polyol production from fossil-based feedstock and lignite-fired power generation. The emissions profile of both conventional polyols and CO_2-based polyols are dominated by the production of the epoxides propylene oxide (PO) and ethylene oxide (EO). The abatement potential of CO_2-based polymers stems from the replacement of PO and EO by CO_2. The avoided emissions per kg of CO_2 utilised are found to range from 1.3 kgCO_2e to 3.0 kgCO_2e for polyols containing 10–30% by weight CO_2 (von der Assen & Bardow, 2014). These findings are consistent with Econic's assertion that for each tonne of CO_2 used as feedstock to manufacture polyols containing 30–50% by weight CO_2 3 tonnes of CO_2 are saved (Econic Technologies, 2016).

4.6 Synthetic methane

Summary of carbon abatement effectiveness indicators

- **Efficiency of CO_2 absorption:** The CO_2 is temporarily stored in the methane.
- **Duration of storage:** Short-lived (weeks). The CO_2 is released upon combustion.
- **Other abatement effects:** Emissions abatement through avoiding the use of natural gas if used directly, or a lower gas grid intensity if injected to the gas grid.
- **Energy input and intensity of processing:** Electricity use for electrolysis. High intensity.
- **Input materials:** H_2 (derived via electrolysis or by-product).

Summary of literature

In terms of carbon abatement, synthetic methane would displace a part of the import and/or production of natural gas. As the CO_2 used to make synthetic methane is released upon combustion, the technology cannot be seen as providing long-term carbon storage. Nevertheless, LCAs comparing value chains (production of natural gas vs. production of synthetic methane) provide an insight in the carbon abatement this technology could bring:

- Sternberg & Bardow (2016) compare Power-to-Gas using CO_2 from a coal fired power plant to conventional natural gas supply using system expansion. The functional unit of the study is 1 MJ of synthetic natural gas (SNG) and 0.048 kWh of electricity. The study finds that the main contributing factor in the carbon footprint of SNG is the supply of electricity for the electrolysis. The threshold value for the carbon intensity of the electricity supply is 82 gCO_2e/kWh. Thus, in case renewable electricity (e.g. wind, solar) is used, the Power-to-Gas process is preferable over conventional natural gas (Sternberg & Bardow, 2016).
- The findings from Reiter & Lindorfer (2015) are very similar, concluding that the environmental break-even point is 113 gCO_2/kWh if utilised CO_2 is treated as a waste product, and 73 gCO_2/kWh if the CO_2 separation effort from a coal-fired power plant is included. When the electricity used to produce the H_2 has a carbon intensity of around 73-113 gCO_2e/kWh or lower, this technology leads to actual CO_2 savings.

Currently (2016), the UK electricity grid carbon intensity is 412 gCO_2e/kWh[20], while DECC projections[21] indicate it could fall to around 100 gCO_2e/kWh in 2030 as generation by low carbon technologies expands. This, however, just gives a very first indication of when this technology would lead to carbon abatement, as in reality one should consider the carbon intensity of the marginal electricity generation technology; this has not further been assessed here.

During the 5 December 2016 workshop, a participant noted that when methane is emitted (for example as a consequence of leaks), the climate impact can be significant as the 100 year Global Warming Potential (GWP) of methane is 25 times that of CO_2. While this is true, it doesn't impact the comparison between natural gas and synthetic methane. It is associated with the continued use of methane though; we haven't assessed the relevance of these emissions here.

4.7 Synthetic methanol

Summary of carbon abatement effectiveness indicators

- **Efficiency of CO_2 absorption:** The CO_2 is temporarily stored in the methanol.
- **Duration of storage:** Short-lived (weeks). The CO_2 is released upon combustion.
- **Other abatement effects:** Synthetic methanol production abates emissions by replacing the traditional method of methanol production of steam reforming fossil fuels (primarily natural gas).
- **Energy input and intensity of processing:** Electricity use for electrolysis. High intensity.
- **Input materials:** H_2 (derived via electrolysis or by-product).

[20] https://www.gov.uk/government/collections/government-conversion-factors-for-company-reporting#conversion-factors-2016

[21] https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/501292/eepReport2015_160205.pdf

Summary of literature

A simplified LCA of synthetic methanol production was performed by von der Assen et al. (2013). The functional unit of this LCA, using the system expansion approach, is the production of 1 t methanol and 1,723 kWh electricity. A CCU system, in which methanol is produced from CO_2 captured from a coal-fired power plant and H_2 produced by electrolysis using wind energy, is compared with a non-CCU reference system, in which methanol is produced via steam reforming of natural gas and electricity is produced in a coal-fired power plant (see Figure 3).

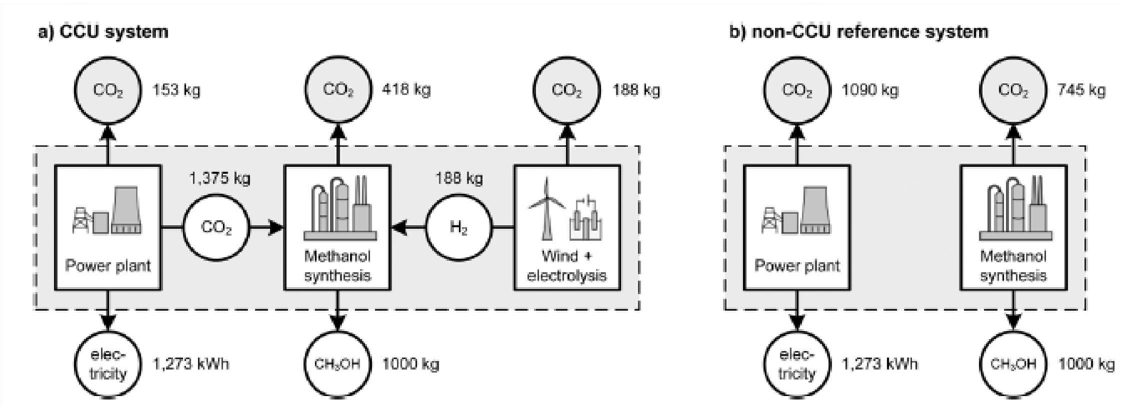

Figure 3. Flow chart and flow quantities (a) for the CCU system and (b) the non-CCU reference system. Source: von der Assen et al., 2013.

The study finds that the CCU system emits 759 kgCO_2e, while the non-CCU system emits 1,835 kgCO_2e. The CCU systems is thus found to be clearly favourable over the non-CCU system, reducing emissions by 59% (Von der Assen et al., 2013). In the simplified LCA, it is assumed that all plants are located closely together and emissions from transportation of feedstock CO_2 are neglected. When assessing the carbon abatement of actual systems, it is important to take the impact of transportation and storage of CO_2 into account. Other key assumptions influencing the results are the characteristics of the point source used for CO_2 capture, the CO_2 capture technology, and the source of the electricity used for compression in the methanol process. (Von der Assen et al. (2013) assume the US grid mix of 550 kgCO_2e/kWh. For comparison the current emission intensity in the UK in 2016 is slightly lower at about 412 kgCO_2e/kWh (as indicated in section 4.6).

Tran et al. (2016) report a carbon footprint of synthetic methanol produced from CO_2 originating from a coke plant of 10.7 gCO_2e/MJ compared to 109 gCO_2e/MJ for conventional natural gas-based methanol, a reduction of 90%. The study considers a coke plant with a power plant, extended with Carbon Recycling International's methanol production process (see chapter 11). The required H_2 is separated out of the coke oven gas via pressure swing absorption (PSA) technology and the CO_2 is captured out of the flue gas of the coke oven battery using post combustion capture. The study uses allocation based on the energy-content of the co-products. Similarly, Péres-Fortes et al. (2015) find an emissions reduction of 91% comparing synthetic methanol to conventional production.

The reported carbon performance of synthetic methanol compares favourably to bioethanol, an alternative fuel that it may compete against. The typical GHG emission saving for sugar cane based bioethanol in the Renewable Energy Directive is 71% compared to fossil fuel.

4.8 Summary

It is evident from this initial review that there is limited data available with which to compare the carbon abatement potential of the selected CCU technologies. We were only able to identify LCA studies for a few of the technologies, while for others we could only identify claims made by technology developers. In addition, the calculation approaches and assumptions taken differed between the studies. This reflects the fact that there is no commonly agreed methodology on how to conduct LCA for CCU. Nonetheless, we are still able to draw some general conclusions of the likely carbon abatement performance of the technologies assessed (as summarised in Table 3).

Table 3. Overview of key carbon abatement performance indicators for the CCU technologies assessed.

Waste stream	Carbonation	Concrete curing	Novel cements	Horticulture	Polymer processing	Synthetic methane / methanol Synthetic methanol
Efficiency of CO_2 absorption	CO_2 is absorbed and locked in minerals	CO_2 is part absorbed, additional CO_2 absorbed during lifetime	CO_2 is part absorbed, additional CO_2 absorbed during lifetime	Portion of CO_2 is stored in crop	CO_2 is temporarily stored in the material (up to 50%)	CO_2 is temporarily stored in the fuel
Duration of storage	Permanent	Permanent	Permanent	Short lived (days, weeks)	Lifetime of the material (years)	Short-lived (weeks)
Other abatement effects	Material displacement	(Claimed) Material displacement	Material displacement	Displacement of natural gas use	Displacement of epoxide use (up to 50%)	Displacement of natural gas use
Energy input and intensity of processing	Depends on process	Limited to energy for CO_2 capture, transport, conditioning	Depends on process	Limited to energy for CO_2 capture, transport, conditioning	Low	High

There is a wide variability in the carbon abatement potential. Carbonation clearly offers the greatest potential, as the CO_2 is locked away permanently. Concrete curing and novel cements also offer good potential, however, any technology that purports to enhance the carbonation of concrete prior to use must be compared on an equivalent basis with the natural capability of concrete to take up CO_2. Polymer processing can store the CO_2 for extended periods (possible decades), but not permanently. However, the process can lead to significant displacement of epoxide use (depending on the level of CO_2 substitution). Although CCU in horticulture can lead to displacement of natural gas use, a limiting factor is that a significant volume of the CO_2 that is added to the glasshouse is vented. Furthermore, the CO_2 that is absorbed in the crop is only temporarily stored. Finally, we find that the carbon abatement potential for the synthetic fuels is lowest. This is a consequence of the high process energy inputs (H_2 production via electrolysis) and that the CO_2 is only temporarily stored.

5 Carbonation technology assessment

5.1 Summary

Carbonation

- **Technology outline and features:** Carbonation technology is based on reacting CO_2 with calcium (Ca) or magnesium (Mg) oxide or silicate to form a solid carbonate mineral structure. These materials can be found both in natural form and in waste streams (the focus of this study). Waste streams include fly ash from combustion, slag from steel production and wastes from cement production. Alternatively, carbonation reactions can use alkaline brines.
- **Market application:** Depending on the input material, a range of products can be produced, primarily materials for the construction industry, such as aggregate, bricks or blocks.
- **Status quo:** The market for secondary aggregates in Great Britain is around 56 Mt and concrete precast products around 22.5 Mt (2013 data).
- **Current technology status:** The TRL level ranges between 4-8. Carbon8 operate two plants, both of which are located in the UK. These each process 30 kt/yr of Air Pollution Control residues (APCr), collectively utilising around 5 kt/yr of $CO_{2.}$ Other active companies include Recoval (Belgium), Skyonic (US), Carbon Clean Solutions (UK), Cambridge Carbon Capture (UK) and Carbon Cycle (UK).
- **Future growth potential:** Carbon8 aim to operate 5 to 6 plants in the UK by 2021 utilising around 19 ktCO_2/yr in total. Additional potential is from cement or steel waste (estimated as up to 27 ktCO_2/yr by 2030), and from one-off soil remediation projects (not quantified).
- **Locations for deployment:** For steel plants, cement plants, or other historical deposits plants are likely to be located at, or near to, the site, whereas for APCr or fly ash the plants are more likely to be co-located next to concrete block manufacturers.
- **Benefits and opportunities:** Carbonation of waste streams has the advantage of treating (hazardous) waste streams. The carbonation of APCr provides an opportunity of (partly) filling the gap of diminishing availability of fly ash from coal fired generation. A potential opportunity for Carbon8 will also arise if the UK bans the landfilling of APCr. A number of carbonation processes can use "raw" CO_2. Carbon8 is among the technology leaders in carbonation, which provides an opportunity for exporting the technology to overseas markets.
- **Barriers and required support:** The availability of sufficient waste materials is possibly the most important long-term constraint, resulting from the decline in steel and coal based power plants in Europe. However, historical waste deposits could potentially still be utilised. A second barrier is that carbonation materials using waste are required to meet the EU End of Waste Regulations. Planning legislation acts as a barrier to plant capacity as above 30 kt/yr plants are subject to national planning approval, which can take up to 36 months. Finally, the building sector is in general conservative and often demand a long-term (up to 15 years) track record before adopting novel products. Investing in trials that demonstrate the long-term durability of the products will facilitate this. A (high) landfill tax supports the business case for this technology.

5.2 Technology outline and features

Industrial carbonation technology is based on reacting CO_2 with calcium (Ca) or magnesium (Mg) oxide or silicate to form a solid carbonate mineral structure. For example, as indicated by one of the following reactions:

(Ca, Mg)SiO_3 (s) + CO_2 (g) → **(Ca, Mg)CO_3 (s)** + SiO_2 (s)

CaOh (s) + CO_2 (g) → **$CaCO_3$** (s) + H_2O (l)

These materials can be found both in natural form[23] and in alkaline waste streams (the focus of this study). Table 4 provides an overview of wastes arising from industrial processes that are suited to carbonation.

Table 4. Overview of waste streams suitable for CO_2 carbonation, building on (Wilcox, 2012).

Industrial process	Alkaline waste
Alumina production	Bauxite residue (red mud)
Cement production	Cement bypass dust (CBD), cement kiln dust (CKD), waste cement
Coal (and biomass) combustion	Fly ash
Construction and Demolition	Construction and Demolition mineral waste (i.e. concrete)
Iron and steel production	Steel slag, blast furnace slag, electric arc furnace slag
Mining	Mine tailings
Pyrotechnics production and use	Contaminated soils
Soap manufacture	Galligu
Waste incineration	Municipal waste incinerator ash / Air pollution control residues (APCr)
Water treatment	Water treatment sludge

These waste streams are frequently stored in landfill, or simply stockpiled on-site. This can present an environmental hazard if allowed to generate dust, or if rain water infiltrates the waste resulting in leaching into groundwater (Gomes et al. 2016). Carbonation with CO_2 presents an opportunity to treat these wastes and create a variety of useful materials that can be used by the construction industry (Renforth et al., 2011).

Depending on the material, carbonation method and temperature, and pre-treatment processes, reported carbonation efficiencies vary from 10 to 60% for untreated natural silicates to 40-90% with heating or mechanical pre-treatment. The carbonation efficiency of artificial silicates is generally reported as >70% without pre-treatment (Renforth et al., 2011). In many cases, these materials present a particle size already suitable for carbonation allowing to reduce, or avoid, the need for an energy-intensive step. Furthermore, energy consumption and costs are reduced as carbonation is an exothermic reaction (Gomes et al., 2016).

Many carbonation processes can tolerate CO_2 at a wide range of purity levels (e.g. 10-90%) although 50-60% is considered to be ideal. However, the lower the purity level the slower the carbonation reaction. (Carey, 2016)

[23] For example, wollastonite, serpentine, and olivine. Carbonation of these materials does not appear to have a future in the UK in the short to medium term, owing to the requirement to mine, crush to small particle size (of the order of microns), react and dispose of vast quantities of rock (estimates from 2-3 times more rock than coal burned in a power station for some rocks, up to 6 times for serpentines) (Fennell, 2013; Nathan, 2015).

Table 5 provides an overview of the carbonation characteristics for CKD, fly ash and steel slag. All of these materials are either Ca or Mg based alkaline wastes.

Table 5. Carbonation characteristics for a selection of industrial Ca or Mg based alkaline wastes (Wilcox, 2012).

Wastes	Characteristics	Temp (^{0}C) and pressure (atm)
Cement kiln dust (CKD)	o 0.15-0.2 t CKD/ t cement. o Typical weight share: CaO (38-50%) and MgO (0-2%).	25; 0.8
Fly ash	o 60% of all coal combustion waste. o Typical weight share: CaO (1-37%) and MgO (1-15%).	30; 10-39
Steel slag	o 10-15% of steel output. o Typical weight share: CaO (32-58%) and MgO 4-10%. o Steel slag is an ideal feedstock for mineral carbonation due to its high alkalinity. o Steel slag is a viable feedstock for cost-effective CO_2 storage option. o Storage capacity is about 0.2-0.25 tCO_2/t steel slag.	100; 18.7

In an alternative carbonation process, UK company **Carbon Cycle** proposes to react gypsum ($CaSO_{4.}H_2O$) with ammonia (NH_3) and CO_2 to produce calcium carbonate ($CaCO_3$) and ammonium sulphate ($(NH_4)_2SO_4$), as indicated by the following reaction:

$CaSO_4{\cdot}2H_2O$ (s) + CO_2 (g) + $2NH_3$ (g) + $2H_2O$ → $\mathbf{CaCO_3}$ (s)+ $3H_2O$ (l) + $(NH_4)_2SO_4$ (s)

According to Carbon Cycle, the gypsum source can either be industrial gypsum, for example arising from scrubbing flue gases at power plants, or naturally occurring gypsum (see section 5.5). The calcium carbonate produced can be either in precipitated (PCC) or ground form (GCC). A schematic of the Carbon Cycle “open cycle” process is shown in Figure 4.

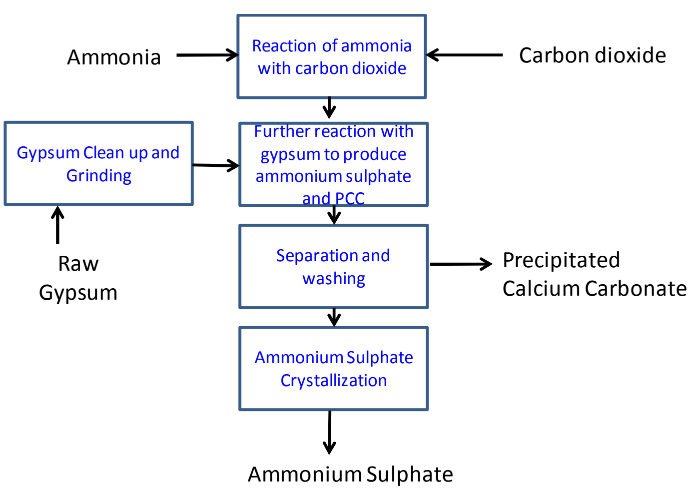

Figure 4. Carbon Cycle “Open cycle” process for the production of PCC (Carbon Cycle, 2016).

Other technology processes involve the carbonation of alkaline brine solutions. US company, **Skyonic**, has developed the SkyMine process which captures and mineralises flue gas CO_2 into sodium bicarbonate/baking soda ($NaHCO_3$). Hydrogen (H_2) and chlorine (Cl_2), or alternatively hydrochloric acid (HCl) are also produced. The process is divided into three parts: gas handling, absorption, and electrochemical production.

In the *gas handling phase*, the hot flue gas is cooled to room temperature, harvesting heat and water while heavy metals, such as mercury, are removed. The harvested heat is used to undertake the cost of chemical production while the water is reused. In the *absorption* phase, the now-cooled flue gas is scrubbed to remove the CO_2 and acid gases such as sulphur and nitrogen oxides (SOx and NOx). In a reaction with sodium hydroxide (NaOH), the CO_2 forms sodium bicarbonate, and the acid gases form sulphate and nitrate salts. The cleaned flue gas is then returned to the exhaust stack. In *electrochemical production*, a feed of salt, water and electricity is used to create the NaOH that is used in the absorption process, as well as the H_2 and Cl_2. Heavy metals, such as mercury, can also be removed by the process.[24]

UK company, **Carbon Clean Solutions**, is also active in this area. In 2016, it commissioned a pilot project that will capture 60 ktCO_2/yr from a 10 MW coal-fired power station based near Chennai, India. The captured CO_2 will be used by Indian firm, Tuticorin Alkali Chemicals & Fertilizers (TACFL), for sodium carbonate (soda ash) production (Na_2CO_3).[25]

In the Netherlands, company **Twence BV** has operated a pilot scale plant to demonstrate the capture of 2 ktCO_2/yr from the flue gas of a waste-to-Energy plant and using it for the production of sodium bicarbonate ($NaHCO_3$) using either sodium hydroxide (NaOH), or sodium carbonate (Na_2CO_3).[26] The company is exploring options to capture 50-200 ktCO_2/yr[27].

UK company, **Cambridge Carbon Capture** is working on a similar technology concept. The first stage involves the low energy digestion of silicate minerals with NaOH to produce low-cost magnesium hydroxide ($MgOH_2$) for the carbon-capture stage. By-products from this initial process include silicon dioxide (SiO_2), and a number of trace metals. The second stage is where CO_2 capture occurs: the exhaust gas is bubbled through a reaction column, in which the $MgOH_2$ reacts with the CO_2 to produce $MgCO_3$. The $MgCO_3$ is then filtered out. The technology is currently at the laboratory scale.[28]

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[24] http://www.epmag.com/carbon-capture-easy-turning-co2-baking-soda-671486#p=full

[25] http://www.carboncapturejournal.com/news/coal-power-plant-in-chennai-sells-co2-for-soda-ash-manufacturing/3818.aspx?Category=all

[26] http://www.co2sbc.eu/shared%20resources/downloads/130724%20Project%20Information%20Sheet.pdf

[27] https://oppex.com/notice/TED_79808fca86dedee197494fb6542e826f

[28] http://www.cacaca.co.uk/

5.3 Market application

Depending on the input material, a range of products can be produced through mineral carbonation (Carbon Cycle, 2016; Carbon8, 2016; BCCF, n.d.), and provide an alternative to conventional production processes. Potential markets include building materials, such as secondary aggregates[29], engineering fill (e.g. in road construction)[30], specialist construction materials (e.g. bricks, blocks, tiles, lightweight aggregate).

GCC and PCC have many potential applications[31].

- **Ground Calcium Carbonate (GCC)** using natural ores, used in a wide array of applications:
  - Adhesives and sealants
  - Animal and pet feeds
  - Carpet-backing
  - Construction (concrete, plasters, asphalt)
  - Environment (desulphurisation of flue gas)
  - Food and pharmaceuticals
  - Glass and ceramics
  - Household products
  - Paints and surface-coatings
  - Paper
  - Plastics and composites
  - Rubber and elastomers
- **Precipitated Calcium Carbonate (PCC):**
  - Cosmetics and toiletries
  - Food and pharmaceuticals
  - Paints and inks
  - Paper
  - Plastics
  - Sealants and adhesives

Sodium carbonate and bicarbonate have multiple market applications.

Sodium carbonate:

- Glass
- Paper
- Detergents/cleaning products
- Sodium bicarbonate

[29] 'Secondary aggregates' are materials which can be used as aggregate but are the waste product of another process. An example is fly ash.
[30] 'Engineering fill' is a material that is used to fill in a depression or hole in the ground, or create mounds or otherwise artificially change the elevation of the ground. These may include earthworks such as infill, raising or levelling ground, embankments, foundation pads, road bases and landscaping.
[31] PCC is produced through a recarbonisation process or as a by-product of a bulk chemical processes. GCC is simply ground chalk or marble. PCC has very specific crystal structures and a tightly defined particle size, as opposed to ground chalk or marble (GCC). PCC therefore commands a higher market price compared to GCC.

Sodium bicarbonate:

- Animal feed
- Food
- Flue gas treatment
- Personal care/pharmaceuticals
- Detergents/cleaning products
- Haemodialysis
- Chemicals

5.4 Status quo

Natural sources, such as chalk, gypsum or limestone, are traditionally used as input materials for building materials or for GCC/PCC market applications. These markets are significant in size:

- The total market of recycled aggregates in Great Britain is estimated in 2013 at 56 Mt (MPA, 2014) (no data was available on what share of this current market relates to lightweight building materials).
- The total market of concrete precast products in Great Britain is estimated in 2013 at 22.5 Mt (MPA, 2014).
- Global market for calcium carbonate products is estimated to be up 96 Mt/yr (Carbon Cycle, 2016; Roskill, 2012). This is split as:
    - PCC: 14-16 Mt/yr
    - GCC: 75-80 Mt/yr
- The UK market for calcium carbonate products is 2 Mt/yr (Carbon Cycle, 2016; Roskill, 2012).

For the production of GCC and PCC, the conventional production process requires high purity chalk, limestone and marble sources, materials that need to be imported into the UK. In contrast, technology developer Carbon Cycle claim that their "Open cycle" process can use any gypsum source which are both abundantly available in the UK.

Recent publically available data on the size of the sodium bicarbonate market is limited, but is estimated to be 2.5 Mt/yr globally. Europe accounts for 25% of the global consumption.[32]

5.5 Current technology status

The TRL level of the carbonation technologies assessed ranges between **4-8**. At TRL 8 is Carbon8's Accelerated Carbonation Technology (ACT) technology. At the lower end are the Cambridge Carbon Capture and Carbon Cycle processes, while the SkyMine process is rated at TRL 6-7.

[32] https://www.icis.com/resources/news/2000/09/18/121774/sodium-bicarbonate-market-braces-for-the-entrance-of-american-soda/; http://www.chemmarket.info/en/home/article/2157/; https://www.ihs.com/products/sodium-bicarbonate-chemical-economics-handbook.html

Carbon8

Carbon8 operate two carbonation plants in the UK, at Brandon (Suffolk) and Avonmouth. Both plants are co-located next to sites operated by the concrete block manufacturer, Lignacite. The plants were commissioned at a cost of around £5m each with a build time of less than six months. Each plant processes 30 kt/yr of Air Pollution Control residues (APCr), the maximum capacity allowed under their permit[33]. The Avonmouth plant, however, has a design capacity of 40 kt/yr, and the site allows further expansion to 60 kt/yr. A third plant was planned for Leeds[34] in 2016, however the planning approval was subsequently withdrawn.

Carbon8's plants collectively utilise around 5 ktCO_2/yr. According to Carbon8, the CO_2 utilisation is currently not fully realised as the CO_2 is sourced from the bulk market at very high purity, and corresponding high cost. If lower purity CO_2 was available (50-60% is ideal) then the uptake could be increased, however at the moment there is no market incentive to do so.

Carbon8 has a contract with Viridor to take APCr, but not with other waste companies. APCr is otherwise treated and disposed to landfill, or stored in salt caverns in Cheshire. As such, Carbon8 can only take a portion of the available APCr that is currently produced. Additional material can only be accessed when the waste management contracts come up for renewal (contract terms are typically between 3 and 10 years).

The process produces a lightweight aggregate material suitable as a construction material. According to the technology developers the aggregate is classified as lightweight, which is an important consideration for the construction industry. The aggregate is, however, not as light as secondary aggregate which has a density of 50% of Carbon8's material. Importantly though, secondary aggregate is reportedly three times as expensive (Carey, 2016).

[See also Appendix 3 for a case study on Carbon8.]

Carbonstone Innovation (Recoval)

Carbonstone Innovation, a company based in Belgium, has developed a process for recycling a fraction of steel slag into construction materials (e.g. aggregates, bricks, tiles and blocks) through the injection of CO_2. In October 2014, the company opened a pilot plant, located at Farciennes. The project cost was around €10.8m, €6.6m of which was provided through regional subsidies.[35]

The process uses a grinding mill to process rough metal slag into a fine fraction (filler) suitable for carbonation (metals can also be recovered). The process can create a wide range of bricks, both hollow as well as solid. The carbonation itself is done in an autoclave under high pressure and temperature. According to Carbonstone this makes it possible to manufacture bricks with strengths exceeding 100 MPa.[36]

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[33] Above 30 kt/yr, national planning approval (National Strategic Planning legislation) is needed as this falls under the hazardous waste regulations. This can take 24-36 months, which is significantly longer than local planning decisions, thereby acting as a constraint to capacity.

[34] http://c8a.co.uk/carbon8-wins-approval-to-build-new-plant-in-leeds/

[35] http://www.recoval.be/i/communique-de-presse-3-10-2014.pdf

[36] https://www.carbstoneinnovation.be/en/carbstone-innovation-nv-about-us/carbstone-innovation-nv-history

Skyonic

In the US, Skyonic has been developing it's SkyMine technology since 2005, which mineralises post-combustion flue gas CO_2 as carbonate compounds (Skyonic, 2016). The company operates a demonstration plant that is co-located next to the Capital Aggregates cement works in San Antonio, Texas. Skyonic commissioned a commercial scale plant in 2014 that can capture 83 $ktCO_2$/yr and produce 160 kt/yr of sodium bicarbonate (baking soda), as well as H_2 and Cl_2, or alternatively HCl.[37]

Carbon Cycle

Carbon Cycle aims to build a commercial scale plant in the UK, located at Teesside, by 2020, although the company announced in October 2016 that these plans are currently on hold (Ecofys & Imperial College, 2016). The plant, if commissioned, would have a production capacity of 191 t/d ammonium sulphate and 91 t/d PCC and capture 40 t/d of CO_2, equivalent to a CO_2 utilisation of 12-13 $ktCO_2$/yr. Carbon Cycle had been in discussion with the utility company Sembcorp to supply the CO_2 (the process can run off dilute CO_2 sources). The indicated plant cost is in the range £15-20m. Carbon Cycle was previously awarded funding under the UK Government's Energy entrepreneurs fund[38].

Other

There is no recent comprehensive overview available of additional stakeholders working on develolping carbonation technologies, but based on previous studies, the amount of stakeholders is estimated to be several tens of companies and research institutes (Ecofys & Carbon Counts, 2013).

5.6 Future growth potential to 2030

Based on current developments, Carbon8's ACT technology is expected to reach **TRL 9** by 2030.

The availability of APCr is set to increase in the coming years as a greater proportion of the UK's household waste is treated via incinerator facilities. According to UK government estimates compiled in 2015, this could rise from around 300 kt/yr to 600 kt/yr by 2020[39]. Carbon8 aim to operate 5 to 6 plants in the UK by 2021, each treating 40 kt/yr APCr (i.e. up to 240 kt/yr equivalent to 40% of the estimated total APCr waste available). The potential uptake of CO_2 in treating 240 kt/yr APCr is about 12-19 $ktCO_2$/yr (assuming 5-8% uptake). Given the potential constraint on access to waste material (as indicated in section 5.5), a CO_2 uptake of 19 $ktCO_2$/yr has also been assumed for 2030.

The Carbon8 process could also treat other thermal thermal waste streams that are reactive with CO_2, including cement kiln dust (CKD), steel wastes and fly ash from coal or biomass power plants (although according to Carbon8 fly ash from UK coal plants is not suitable). The CO_2 uptake varies between these waste materials, but is typically between 10-25%. Steel slags could take up as much as 30% (Carey, 2016). We estimate an additional potential of up to 24 $ktCO_2$/yr (assuming 20% uptake) by 2030, based on 3 plants each treating 40 kt/yr either CKD or steel waste (i.e. 120 kt/yr in total). Additional potential could arise from one-off soil remediation projects, such as at the proposed Paramount development at Swanscombe in Kent, which has historical cement deposits.

[37] https://www.bloomberg.com/news/articles/2013-06-25/bp-backs-texas-carbon-capture-as-skyonic-gets-128-million-funds

[38] https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/275101/EEF_Company_and_Project_Summaries_Phases_1_2.pdf

[39] See: http://www.airqualitynews.com/2016/04/14/rule-change-sought-on-air-pollution-control-residues/

The aggregate market is fairly flexible and already use waste materials, and so this is not seen as a barrier. Carbon8 assert that they could potentially supply a maximum of 3-5% of the UK aggregate block market, and so overall this represents a relatively small market impact (Ecofys & Imperial College, 2016). The on-going closure of UK coal plants also provides an opportunity to fill the gap from the lack of fly ash material from coal fired generation that is currently used for aggregates[40].

Table 6 shows an overview of the estimated availability of waste streams both in the UK and globally. It should be noted that the basis for some of these estimates are several years old. Consequently for some UK waste streams (specifically for iron and steel slag, fly ash and flue gas desulphurisation) these represent an overestimate due to the closure of plants in recent years.

Table 6. Overview of the estimated availability of alkaline waste streams in the UK and global and CO_2 abatement potential. Note that historical waste sources may have already partially carbonated.

Waste stream	UK	Global	Theoretical CO_2 abatement potential
Ironwork slag	3 Mt/yr (Renforth et al., 2011)	250-300 Mt/yr and 7,900-9,500 Mt historical since 1875 – 80% potentially reused (Renforth et al., 2011)	0.42 $MtCO_2$/Mt (Renforth et al., 2011)
Steelwork slag	1 Mt/yr (Renforth et al., 2011)	170-250 Mt (Gomes et al., Alkaline residues and the environment: a review of impacts, management practices and opportunities, 2016) 130-200 Mt/yr and 4,200-6,400 Mt historical since 1875 (Renforth et al., 2011)	0.42 $MtCO_2$/Mt (Renforth et al., 2011)
Fly ash (coal combustion)	5.3 Mt (DEFRA, 2015) 6 Mt/yr (Renforth et al., 2011)	415-600 Mt (Gomes et al., Alkaline residues and the environment: a review of impacts, management practices and opportunities, 2016) 198-383 Mt/yr and 7,600-14,600 Mt historical since 1875 (Renforth et al., 2011)	0.03-0.23 $MtCO_2$/Mt - range reflects coal type: lignite ash (low bituminous (high) as (Renforth et al., 2011)
Flue gas desulfurisation waste (predominantly gypsum)	No data identified	11 Mt/yr (Gomes et al., Alkaline residues and the environment: a review of impacts, management practices and opportunities, 2016)	No data identified
Air pollution control residues (APCr)	0.27-0.46 Mt/yr – 2015 0.33-0.56 My/yr – 2020 (DEFRA[41])	1.2 Mt (Gomes et al., Alkaline residues and the environment: a review of impacts, management practices and opportunities, 2016) (EU only – based on 2.54% of waste incinerated)	0.03-0.10 $MtCO_2$/Mt (Carey, 2016)
Cement waste	No data identified	420–568 Mt (Renforth et al., 2011) (Cement kiln dust)	0.51 $MtCO_2$/Mt (Renforth et al., 2011)
Mineral waste from construction & demolition	45 Mt/yr - 2012 (DEFRA, 2015)	497-2,095 Mt (Gomes et al., Alkaline residues and the environment: a review of	0.08-0.11 $MtCO_2$/Mt (Renforth et al., 2011)

[40] The UK government is currently consulting on plans to close unabated coal fired generation by 2025, see: https://www.gov.uk/government/consultations/coal-generation-in-great-britain-the-pathway-to-a-low-carbon-future

[41] Personal communication with Jane Stratford (Defra). Estimates are based on assumed future energy from waste capacity and the assumption that APCRs are generated at somewhere around 3-5% of the input material.

Waste stream	UK	Global	Theoretical CO_2 abatement potential
		impacts, management practices and opportunities, 2016) 1,400-5,900 Mt/yr (Renforth et al., 2011)	
Fines from aggregate production	No data identified	3,300 Mt/yr (Renforth et al., 2011)	0.06 $MtCO_2$/Mt (Renforth et al., 2011)
Mine and quarry waste	25 Mt/yr - 2012 (DEFRA, 2015)	2,000-6,500 Mt/yr (Renforth et al., 2011)	No data identified

Globally, it is estimated that over 2 billion tonnes of alkaline waste is being produced annually, with around 90 billion tonnes produced since industrialisation (Gomes et al. 2016). According to Gomes et al. (2015) if all waste materials that contain silica (cement, construction and demolition wastes, slag, ash and combustion products) were carbonated, the CO_2 uptake could be **697-1,218 Mt/yr**.[42] Steel slag alone could capture 170 $MtCO_2$/yr.

According to Carbon8, it is assumed that from this potential about **200 Mt/yr** can realistically be carbonated, based on CO_2 availability (at the right quality and price) and that the waste is near to the market for building products. (A gate fee is also important for the business case.) The associated CO_2 demand would be around **15 $MtCO_2$/yr** (Carey, 2016).

In terms of carbon abatement, this depends on the availability of waste material, the energy required for treatment, grinding, handling and transportation is an important factor. At ambient temperature and normal atmospheric pressure, most of the carbonation reactions for silicate waste streams will be thermodynamically driven to occur (Renforth et al., 2011), but may be slow, for a variety of reasons However, the mechanisms depend on kinetic factors as well, including dissolution rate and reactive surface area. This can negatively influence the free energy. In addition, the waste streams consist of mixtures of minerals, which can reduce the potential for carbonation.

For the production of PCC, the reaction reportedly occurs at ambient temperatures. According to Carbon Cycle the products (PCC and Ammonium sulphate) produced by its process would reportedly have a 20% less carbon footprint compared to the conventional processes (Ecofys & Imperial College, 2016). However, the underlying basis for this estimate could not be verified. For example, it is not understood whether the energy requirements for CO_2 capture, purification (if relevant) and transportation are included in this assessment.

[42] According to (Renforth et al., 2011), approximately 7-17 billion tonnes are produced globally each year with an approximate annual sequestration potential of 190-332 Mt C. This is a theoretical potential as this would assume that all available calcium and magnesium in the waste streams will be fully carbonated, which is unlikely in practice.

Key findings on carbon abatement impact based on a literature review and interviews include:

- The maximum CO_2 abatement based on the availability 7-17 bt of silicate waste streams is estimated at 190-332 $MtCO_2$/yr (Renforth et al., 2011). This is a **theoretical potential** as this would assume that all available calcium and magnesium in the waste streams will be fully carbonated, which is unlikely in practice.
- On a global scale, 1.2 Mt/yr APCr is available, which could utilise 60 $ktCO_2$/yr (Carey, 2016; Gomes et al., 2016).
- The potential CO_2 abatement from treating 240 kt/yr APCr in the UK is estimated at 12-19 $ktCO_2$/yr (access to sufficient waste material may constrain growth). An additional, 24 $ktCO_2$/yr is estimated for treating cement and steel wastes.
- A Carbon Cycle plant (if commissioned) would utilise around 12-13 $ktCO_2$/yr.

5.7 Locations for deployment

For the locations of carbonation plants, three factors are particularly relevant:

- **Proximity to market:** For APCr the plants are more likely to be co-located with concrete block manufacturers (i.e. where the market for building products is) rather than with waste-to-energy plants. A key consideration is that aggregate volume is twice the volume of the ash, and so this approach minimises transport costs.
- **Availability of waste streams:** For steel plants, cement plants, or historical deposits plants are likely to be located at, or near to, the site where the waste is located.
- **Availability of CO_2 infrastructure:** Depending on the quantities and the location, the CO_2 can be supplied by:
  - Truck: in case of smaller volumes (as is the case with Carbon8 currently).
  - Pipeline: in case of a cluster approach, where a CO_2 pipeline infrastructure is economically feasible.

In the UK, the Teesside Collective see very good opportunities for mineral carbonation in their region. The region has availability of CO_2 at different purity levels and also significant availability of waste materials, such as historical steel slag deposits. Both Carbon8 and Carbon Cycle have explored the possibility of locating plants at Teesside. Other (former) industrial regions would also be well suited for the technology.

Alternatively, the technology could function as a stand-alone plant outside of industrial regions, co-located with modest scale sources of CO_2. Two Carbon8 plants are currently operational in the UK (located at Brandon and Avonmouth), although these plants currently utilise CO_2 supplied by truck. As indicated in section 5.6, Carbon8 aim to have 5-6 plants in operation by around 2021 in the UK each with a capacity of 40 kt/yr. Potential identified locations include: Leeds, Kent, Midlands, Teesside, Northern Ireland and Scotland. However, the challenge will be to access sufficient waste material.

Existing locations are indicated in the map presented in chapter 6 (see Figure 5, page 42).

5.8 Benefits and opportunities

Carbonation of waste streams has the advantage of treating (hazardous) waste streams, by carbonating CO_2 to create useful products, such as aggregates and other building materials.

In the UK, the carbonation of APCr provides an opportunity of (partly) filling the gap in the aggregate market due to the diminishing availability of fly ash material arising from coal fired generation that has typically been used. A potential future opportunity for Carbon8 will also arise if the UK bans the landfilling of APCr.[43]

A number of the carbonation processes can make use of “raw” CO_2 and utilise CO_2 concentrations between 10-90%. This offers potential for using sources of CO_2 that are not suitable for other CCU applications (or would need to be conditioned / purified first).

[43] This was subject to a consultation by the Environment Agency in February 2014, see: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/538446/Phasing_out_Waste_Acceptance_Derogations_-_Consultation_document.pdf. A decision on this consultation has not been taken at the time of writing this report.

Considering the size and volume of individual plants, the technologies would be particularly suitable for development in industrial clusters, where CO_2 and input materials (i.e. waste streams and natural sources) are available. An example is the Teesside Collective, who have being in contact with both Carbon8 and Carbon Cycle to develop locations at their industrial cluster. Clustering of these technologies could initiate the deployment of both carbon capture technologies in the industrial area, as well as CO_2 infrastructure.

With two operating plants, the UK is among the technology leaders in one of the carbonation technologies. This offers opportunities for exporting the technology to overseas markets.

For carbonation technologies concerning PCC production, the US market appears to be potentially interesting. In 2012, the US production of GCC was estimated at 15 Mt (20% share of global demand) and 3 Mt of PCC (20% share of global market) (Roskill, 2012).

5.9 Barriers and required support

The availability of sufficient waste materials is likely to be the most important long-term constraint. The number of steel and power plants in the UK and in Europe are decreasing. In addition, unabated coal plants are set for closure in the UK and elsewhere. This means that less waste will become available for carbonation, although historical waste deposits could potentially still be utilised.

An exception is the availability of APCr which is expected to increase in the coming years as more waste-to-energy plants are commissioned, however this waste stream is relatively small compared to other waste streams. Furthermore, the volume of APCr generated per plant *may* decrease if the trend for lime recycling (in order to reduce lime costs) at waste-to-energy plants becomes established practise in the UK[44]. Carbon8 indicate that a high degree of recirculation might not be cost effective as it makes the APCr very sticky, leading to blocked storage silos and pipework, and potentially resulting in plant shutdown in an extreme case. As such, the position is not fully clear at this time.

A second barrier is that carbonation materials made from wastes are required to meet the EU End of Waste Regulations in order for the end-product to be sold into the block market. The Environment Agency does not permit products to be marketed if made from certain waste streams (Ecofys & Imperial College, 2016). A further complication is that at a European level, these regulations are not applied consistently, which serves as a barrier to investment. This effectively limits export of the technology to those Member States where Carbon8 aggregate meets the regulations.

UK permitting legislation currently only allows the use of so called “Chapter 19” waste streams from waste-to-energy plants, and prohibits the use of other waste streams (e.g. “Chapter 10” waste streams such as fly ash from biomass combustion). Planning policy also serves as a barrier. Above 30 kt/yr capacity plants fall under the hazardous waste regulations, which requires national planning approval. This can take up to 24-36 months, compared to only several months for local planning approval (Carey, 2016).

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[44] Personal communication with Dr Thomas Schlegel (EESAC).

Similar to CCU concrete curing or novel cements (see chapters 6 and 7), the conservative nature of the building sector may limit the uptake of carbonate products in the short to medium term, as consumers are typically reluctant to adopt new building materials that do not have an established track record (up to 15 years). As a mirror image of the hurdle that this creates for market adoption, there is currently little market pull / value for low carbon products from the construction sector. Further research is required on engineering properties and material characteristics, to be able to warrant the long-term performance and durability of these materials. This is an important factor in the scope for application.

A further potential barrier is that some waste streams (such as APCr) contain potentially high traces of heavy metals. This poses an issue with being able to guarantee that there will be no leaching. Stakeholders at the 5 December 2016 workshop also indicated that the uptake of these waste streams may lead to some public opposition, as people might not like the fact that these type of waste streams are used for building materials. It is important to note, that many ingredients for aggregate blocks actually have high trace elements in any case (for example, crushed bricks). Nonetheless, this is a potential issue that could inhibit market adoption

Finally, the cost for capturing and transporting CO_2 is a hurdle, depending on the volume and location, an infrastructure with trucks and/or pipelines are required. Currently there is no CO_2 infrastructure in the UK for CO_2 from industrial flue gases.

Potential ways to address these barriers and incentivise deployment include:

- Continue to support a (high) landfill tax to encourage the use of waste streams.
- Place a value for the CO_2 captured (to maximise CO_2 uptake).
- Assess permitting and planning legislation with respect to CCU technologies.
- Investing in trials that demonstrate the long-term performance, durability and safety (with regard to potential leaching) of the products.
- Increase public awareness of CCU products (e.g. through a labelling system).
- Undertake a comprehensive mapping of potential UK alkaline waste streams.
- Introduce tax incentives for using building materials produced with CCU technologies.
- Provide preferential procurement of these products by government bodies.

6 Concrete curing technology assessment

6.1 Summary

Concrete curing
• **Technology outline and features:** Concrete curing in general refers to the hydration process of various elements within the cement that is part of the concrete mix. Ordinarily, this leads to the development of strength via the production of calcium hydroxide $Ca(OH)_2$. The cement can be carbonated by injecting gaseous CO_2 through it as it sets. This is analogous to the natural carbonation process for cement, but many times faster. • **Market application:** The technology is applicable to concrete masonry (blocks) or ready mixed concrete. In both cases, the CO_2 is added when the concrete is mixed. The technology can be applied to any existing precast concrete plant, with modest investments needed. • **Status quo:** Portland cement based concrete and mortars are widely used and have a long track record in the UK building sector. • **Current technology status:** The TRL level for is currently 7-8. There are a few companies working on developing this technology, although no specific UK owned companies were identified. Canadian company, Carbon Cure, has developed technologies where CO_2 is injected during the concrete mixing phase. The technology is not widely deployed as yet. • **Future growth potential:** According to Carbon Cure, with their technology fully optimised and implemented the CO_2 demand for the UK is 100 ktCO_2/yr. There is potential for large-scale deployment by 2030, though this outlook is based on the assumption that concerns about variability or deterioration in long-term cement chemistry affecting the durability of steel reinforcement have been allayed. Alternatively, the technology could be constrained to the significantly smaller market for non-reinforced concrete blocks and non-structural concrete. • **Locations for deployment:** For CCU in pre-cast concrete production, the technologies for the production of pre-cast concrete are considered add-on technologies. These can be installed in existing concrete plants. Ready-mix concrete that is used for in-situ casting on the building sites spread over the country. For this case, there are no specific location factors, as CO_2 would likely need to be transported in these cases by truck. • **Benefits and opportunities:** The main benefit of the technology is that the cement produced is claimed to be stronger. Purported advantages include stronger and denser produced cement. There is a marginal uptake of CO_2 per tonne of cement produced (around 1.5% CO_2 by weight), though given the large volume of cement produced this adds up to a large overall figure. • **Barriers and required support:** Long-term strength of the produced cement has not been proven over the course of many years. Assistance with long-term testing (including potential corrosion of steel reinforcing) would be valuable. If it is indeed proven that the carbonation technology has significant benefits for strength, the market should develop naturally as further testing leads to confidence in the product.

6.2 Technology outline and features

Concrete curing in general refers to the hydration process of various elements within the cement that is part of the concrete mix. Ordinarily, this leads to the development of strength via the production of calcium hydroxide ($Ca(OH)_2$). Some companies (e.g. Carbon Cure) and researchers have proposed that *carbonation* can take the place of hydration during the curing phase, to produce solid calcium carbonate ($CaCO_3$), which significantly increases the short-term take-up of CO_2. This offers permanent sequestration of the bound CO_2. The chemical processes are as follows[45]:

$$CaO\ (s) + CO_2\ (g) \rightarrow \mathbf{CaCO_3}\ (s)$$

$$Ca(OH)_2\ (s) + CO_2\ (g) \rightarrow \mathbf{CaCO_3}\ (s) + H_2O\ (l)$$

This process occurs naturally in regular concrete, but very slowly as CO_2 from the air penetrates the concrete at a rate of some mm/year[46]. However, in the case of a CCU application, the aim is to greatly accelerate this process in a way that allows the use of CO_2 that is captured from industrial sources. CO_2 can be injected (sparged) as part of the concrete mixing process, which may be complemented by curing chambers with elevated CO_2 concentration in the case of pre-cast concrete.

In terms of carbon abatement effect, it is important to (a) note that concrete stores the CO_2 permanently, and (b) consider the natural CO_2 absorption by regular concrete over time as a reference situation.

A key potential limitation with concrete curing is associated with changing the long-term alkalinity of the concrete pore-water in the case where the cement is used in reinforced concrete (the main market for concrete products). This is important since the natural carbonation of concrete causes the alkalinity of the concrete pore water to drop, allowing corrosion of reinforcement steel by atmospheric oxygen and destroying the strength and durability of the concrete over time. Though assurances have been given through the production of a technical note by Carbon Cure that the pore water remains at the same alkalinity after 28 days, far longer trials with concrete *in-situ* are required to “prove” that the pore water remains at the same alkalinity over the typical lifetime of a structure, which can be up to 50 years. Furthermore, as the construction industry tends to rely on proven concepts and long-established standards and codes, substantial effort and time will be required to work towards broader adoption.

Globally, a handful of companies, universities and research institutes are developing concrete curing technologies, while there is a conference series devoted to accelerated carbonation technologies of all types (including those discussed in chapter 5 (ACEME, 2015). In this study, we reviewed a range of literature sources[47] and furthermore interviewed a number of technology developers.

[45] Note that ordinary Portland cement (OPC) has a large number of constituent components. We are interested in the carbonation of the CaO / $Ca(OH)_2$ components.

[46] Quantification depends on many aspects, including whether the concrete is exposed or not, humidity, temperature and the exact concrete properties.

[47] (Ali & Dunster, 1998), (Parott, 1987), (Parrott & Killoh, 1989), (Cabrera & Woolley, 1985), (Houst & Wittmann, 2002), (Litvan & Meyer, 1986)

6.3 Market application

The products of concrete curing CCU technologies can be used in the building sector, primarily along two routes:

- prefabricated concrete elements or blocks produced in concrete pre-casting plants, or
- ready-mix concrete or mortar used on building sites (in-situ) either for casting concrete parts.

The technology is applicable to concrete masonry (blocks) or ready mixed concrete. In both cases, the CO_2 is added when the concrete is mixed. The technology can be applied to any existing precast concrete plant, with modest investments needed.

A key limitation for the applicability, at least up to 2030, is the need for these concrete products to achieve proven structural characteristics and durability. In particular, due to the potential issue with reduced alkalinity affecting reinforcement steel[48], this makes it likely that this type of concrete will be constrained to applications of non-reinforced concrete.

On the other hand, there is the potential for concrete curing technologies to result in higher strength concrete, while reducing the time of the curing/weathering process and reduce the demand for cement – the most costly part of the concrete mix. This could potentially result in lower costs of concrete (Wagner, 2016). As the construction industry is very competitive, the market value and profitability of the concrete curing technologies and the projected abatement costs will strongly depend on these characteristics and applicability of the concrete products.

With respect to sources of CO_2, some of the technologies have been using purified CO_2 (Carbon Cure, 2016) (transported in liquid form), while this technology may allow for using some less pure forms of CO_2.

6.4 Status quo

Portland cement based concrete and mortars are widely used and have a long track record in the UK building sector, making use of an extensive body of codes and standards with detailed specifications for the required material properties, handling procedures, quality assurance and testing standards and structural design requirements.

The total UK market for precast and ready-mix concrete is substantial and has been growing in recent years (MPA, 2014):

- Ready-mix concrete production: 15 Mm^3 (40 Mt) in 2013 (estimated 75% of the market).
- Precast concrete production: 7 Mm^3 (2.5 Mt) in 2013.

In broad terms and for most applications, the building industry is conservative and will only accept new building materials that do not have a long-term proven reliability and established standards and practices for production and handling.

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[48] This can also be an issue with natural carbonation, except that the process is significantly slower (taking decades).

6.5 Current technology status

The TRL level for injection of CO_2 during mixing phase is currently **7-8**.

There are a few companies working on developing this technology, although no specific UK owned companies were identified. A leading proponent of concrete curing is the Canadian company **Carbon Cure** who are developing proprietary technologies where CO_2 is injected during the concrete mixing phase, specifically for:

- Masonry, where CO_2 is injected into wet concrete while it is being mixed. Once injected, the CO_2 reacts with cement components to form $CaCO_3$. The technology is integrated with the producer's batching system and has no impact on normal operations (Carbon Cure, 2016)
- Ready-mixed concrete, works essentially the same as for masonry, although here the CO_2 is injected into the wet concrete on site (Carbon Cure, 2016).

Carbon Cure currently has over 30 customers deploying its technology, primarily in the US (the company's main focus). The technology can reportedly by applied to any existing concrete facility as an "add-on" technology, without major investments required. (Wagner, 2016)

6.6 Future growth potential to 2030

The TRL level for injection of CO_2 during mixing phase in 2030 is expected to be **TRL 9**. This outlook is based on the assumption that concerns about variability or deterioration in long-term cement chemistry affecting the durability of steel reinforcement have been allayed. Alternatively, the technology could be constrained to the significantly smaller market for non-reinforced concrete blocks and non-structural concrete.

Worldwide production of concrete is estimated at around 20 billion tons per year (Oss, 2016), which is about 8,000 Mm^3 of concrete. This would have a natural uptake at steady state of very approximately 100-200 $MtCO_2$/yr (approximate calculations by Imperial College). According to Carbon Cure, the total CO_2 reduction from their technology could be 750 $MtCO_2$, including the effect of using less cement as it is stronger (although this reduction opens up a host of potential questions, such as the baseline cement content of the concrete, replacement of components within the cement by others, etc. (Won, Kim, & Lee, 2015), (Pérez-Carrión, et al., 2014)).

According to industry reports, the European volume of concrete products is estimated at 613 Mm^3 per year (Wagner, 2016). Based on these figures, the natural CO_2 uptake would be in the order of 60 Mt/yr. According to Carbon Cure, with their technology fully optimised and implemented throughout Europe, the estimated CO_2 demand for Europe would be 3.8 $MtCO_2$ and for the UK is **100 $ktCO_2$/yr**[49] (Wagner, 2016). As a comparison, the theoretical maximum CO_2 uptake from available concrete waste in the UK is around 500 $ktCO_2$/yr (Hills & Fennell, 2016).

[49] This assumes that a typical plant utilises approximately 250 tCO_2/yr.

In terms of carbon abatement, any technology that purports to enhance the carbonation of concrete prior to use must be compared on an equivalent basis with the natural capability of concrete to take up CO_2 in any case (Hills & al). It is assumed that the CO_2 carrying capacity of concrete is very roughly 0.1 tCO_2/m^3 (Hills & Fennell, 2016)[50] depending on the cement blend used. The CO_2 taken up by the concrete is a natural process and thus occurring also without applying the specific technologies.

In terms of carbon abatement, concrete curing technologies offers a long-term CO_2 reduction potential in the UK of the order of $MtCO_2$ per year. This only refers to the abatement of adding CO_2 into the product, it does not take into account energy penalties (for CO_2 capture and transportation), or the natural uptake of CO_2. Concrete curing technologies will permanently store CO_2 that is being added during the process, either by using different cement, adding CO_2 during the mixing phase, adding an excess of CO_2 during the curing / weathering phase or other options.

While some of the technology developers claim very high GHG emission reductions compared with regular concrete, no documented basis for these claims was found, while no detailed LCA analysis focussing on concrete curing were identified.

In terms of abatement costs, some companies working on concrete curing technologies claim to be able to contribute to reducing CO_2 emissions at a cost less than 4 £/t CO_2 (Wagner, 2016).

6.7 Locations for deployment

For CCU in **pre-cast concrete** production, the technologies for the production of pre-cast concrete are considered add-on technologies. These can be installed in existing concrete plants. The pre-cast concrete plants that are currently operating are therefore considered to be the most economically attractive locations for investing in this technology. The map below gives an impression of where concrete plants can be found in the UK (Figure 5). Some of these are reasonably near to industry clusters with potential availability of infrastructure for transporting the CO_2. Otherwise, the CO_2 would need to be trucked in.

For CCU in **ready-mix concrete** that is used for in-situ casting on the building site the technology will be located at/near to the site (note that ready-mix concrete has an average delivery distance of less than 8 miles in the UK). The CO_2 would likely need to be transported in these cases by truck which would add additional cost, and furthermore impact the carbon abatement potential.

[50] http://info.carboncure.com/white-papers/overview-of-carboncures-masonry-technology-system-trial-results

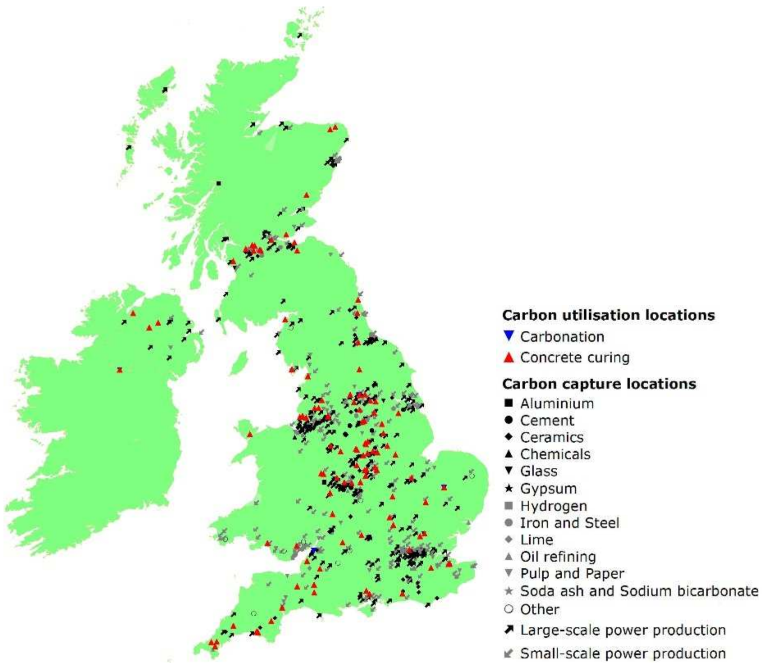

Figure 5. Map showing emission sources and the locations of concrete plants in the UK, including producers of pre-cast and ready-mix concrete. A full-page map is included in Appendix 4.

6.8 Benefits and opportunities

Concrete curing technologies provide the opportunity to permanently store CO_2 in cementitious building materials. While there are no UK-owned companies active in this field, international companies have expressed interest to deploy this technology in the UK.

Substantial volumes of concrete and cementitious mortars are used every year in the UK. Even as this CCU technology is likely be constrained to non-reinforced concrete in the medium term, that market in itself offers a sizeable potential of around 100 $ktCO_2$/yr. Furthermore, there are niche markets for pre-cast concrete product with their specific specifications and requirements that can be tested, warranted and marketed on their own terms.

Concrete is produced (mixed) and installed (cast) in many different locations, including both sizeable industrial pre-casting plants and numerous building sites. This offers the opportunity to co-locate larger scale pre-casting plants near to CO_2 sources, or to focus on those locations where existing plants are near to clusters where CO_2 can be made available. Secondly, applications on building sites around the country, offer the opportunity to use CO_2 from stand-alone sources, that could supply building sites in their region, with CO_2 being transported by truck.

Finally, there are indications that this technology can lead to stronger concrete, allowing construction with lower concrete with reduced cement content and therefore lower cost. In the competitive building sector, this could become an important selling point, when these materials have proven their structural characteristics and durability.

6.9 Barriers and required support

The primary barrier for CCU in concrete curing is that it is necessary to demonstrate that novel concrete curing technologies lead to reliable performance and/or lower material costs for the same performance prior to adoption in the (conservative) building sector. As the building industry relies on an extensive body of quality standards, building codes, contractual norms and established practice, early stage adoption should target less demanding applications. Effectively, CCU-cured concrete is a novel product that will have to earn its place in the market before it can be adopted for widespread application. There is unlikely to be a strong market pull, unless the material can become more cost effective due to better strength characteristics, as some technology developers are currently promising for the future.

As part of this, guarantees, assurances and insurability are extremely important, in particular for structural applications. It is not yet clear to what extent and at what point in time the technology providers can provide such guarantees. For non-structural applications some requirements may be somewhat less stringent, but still relevant. Therefore, it is likely that this niche market could be among those targeted first.

One of the key drivers for this barrier is the potential impact of CO_2 mineralisation on the long-term alkalinity of the concrete pore water which is expected to have a substantial detrimental effect on the durability of the reinforcement steel and subsequently, the strength of the concrete. CO_2 can react with $Ca(OH)_2$ in the pores, neutralising the alkalinity, which in turn removes a protective outer layer on the outside of steel, and allows corrosion by atmospheric oxygen. Although some suppliers assessed the effect of CO_2 on the pH of the concrete and claim that the pore fluid/solution is not affected by the technology, these tests have only been done for a short amount of time (in the case of Carbon Cure, 28 days). For use in structural concrete, long-term durability has to be warranted, which requires testing for periods of at least 15-20 years. This does not mean that the resulting materials cannot be used for construction, but it would seem to be premature to be used for reinforced concrete. This will however constrains the market potential at least up to 2030 for the technologies to non-reinforced concrete.

There is recent academic literature (Jang, Kim, Kim, & Lee, 2016), based on laboratory scale testing, which suggests that the porosity of concrete which undergoes CO_2 curing is significantly lower. This means that it is much more difficult for gases to diffuse through, and may mitigate untoward effects on reinforcing by preventing oxygen diffusion.

Finally, it is necessary to determine how much CO_2 is captured and how much released, when cement is treated. It is furthermore notable that the amount of CO_2 utilised in the process is quite small per tonne of product (i.e. 0.1 tCO_2/m^3).

Some further barriers are associated with cost:

- **Cost for installations to add CO_2 to the curing process** as plant owners need to invest in modifications and the plant will have to be shut down for a short period.
- **CO_2 infrastructure / supply costs**, depending on the volume and location, an infrastructure with trucks and/or pipelines is required. Currently there is no CO_2 infrastructure in the UK for CO_2 from industrial flue gases.

With respect to regulatory barriers, the waste disposal regulations may be relevant for the CO_2 absorbed and the end of life handling of the concrete.

Potential ways to alleviate these barriers are to:

- Promote long-term (5, 10, 20 year) trials in the UK on a range of applications, including intensive monitoring of material performance, including the active involvement of the building sector and organisations responsible for maintaining the standards and codes.
- Inclusion of the products in the building codes to provide confidence of their reliability to the market. This is considered an option for the longer term and will partly depend on the outcomes of additional testing for the reinforced concrete.
- Provide financial incentives to install the technology.
- Introduce tax incentives for using building materials produced with CCU technologies.
- Provide preferential procurement of these end products by government bodies to stimulate their uptake.

7 Novel cements technology assessment

7.1 Summary

Novel cements
• **Technology outline and features:** Though ordinary Portland cement is used in the overwhelming majority of cement applications, there are other types of cement available, and some researchers and a small number of companies are looking to develop cements which use CO_2 as an ingredient. The CO_2 is locked in the cement as a solid carbonate. The mineralisation of CO_2 within the novel cements of interest is typically associated with the primary bonding reaction that generates the strength of the cement, in many cases utilise magnesium minerals. This process can be fed with CO_2 that was captured from industrial sources or local emitters. • **Market application/Staus quo:** There are strong parallels with concrete curing CCU. • **Current technology status:** The current TRL for novel cements is in the range of 3-6. Novacem and Calera were companies working on developing such cements. However, neither were successful, with Novacem filing for bankruptcy with the rights to the intellectual property developed being purchased by an Australian/UK company, Calix. Solidia is another company in the arena, that uses a patented cement that reacts with CO_2 and water to create “Solidia concrete”. • **Future growth potential:** The TRL for novel cements may reach TRL 6-8 by 2030, provided that concerns about variation in long-term cement chemistry and economics have been allayed. • **Benefits and opportunities:** The benefits and opportunities for novel cement are very similar to those discussed under concrete curing CCU. • **Locations for deployment:** It is likely that plants would be based near to a port since we are unaware of any significant magnesite deposits in the UK (i.e. magnesite would need to be imported) and co-located with industrial sources of CO_2. No specific regions have been identified by Solidia, although the company has reportedly been in discussion with Teesside to date. • **Barriers and required support:** While conceptually, barriers for novel cement are very similar to those for concrete curing CCU, the following two aspects apply even more strongly than in the case of concrete curing CCU. 1. It is necessary to prove that novel cement technologies lead to reliable performance and/or lower material costs for the same performance for adoption in the conservative building sector. As the building industry relies on an extensive body of quality standards, building codes, contractual norms and established practices. As part of this, guarantees, assurances and insurability are extremely important, in particular for structural applications. 2. There is unlikely to be a strong market pull, unless the material can become more cost effective through better strength characteristics. For non-structural applications some requirements may be somewhat less stringent, but still relevant. Therefore, it is likely that this niche market could be among those targeted first.

7.2 Technology outline and features

While there are some parallels with concrete curing CCU (described in the chapter 6), another way to bind CO_2 in building materials is to use novel types of cement in the concrete or mortar, other than the Portland cement commonly used today. While some CO_2 is also bound in regular concrete over time, in that case this is a secondary effect while the primary cementitious bonding reaction is hydration.

In contrast, with CCU through novel cements, the mineralisation of CO_2 to cement is typically associated with the primary bonding reaction, in many cases utilising magnesium (Mg) minerals. This process can be fed with CO_2 that was captured from industrial sources or local emitters. There is no specific information available on quality requirements for the CO_2, however it is likely that it is not necessary for it to be of very high purity. For example, Huijgen (2007) indicates that captured flue gas can be used directly[51].

Mg cements can be produced from magnesium oxide (MgO) and other materials. However, compared to Portland cement, the phase diagram of cement formulations are not yet well established. There is no analogy to the formation of cement clinker, most likely because of the propensity of MgO to phase separate at high temperature rather than form high temperature gels, or form unreactive ceramics. Furthermore, the slow hydration of high temperature MgO provides a major challenge, which means that the cements produced will not remain workable for sufficient time to be utilised for building.

A key constraint results from the fact that the abundance of precursors for MgO production is not diverse, unlike limestone, silica and clays in the case of Portland cement. By contrast Magnesite is relatively rare, and synthetic MgO made from precipitation of magnesium hydroxide ($Mg(OH)_2$), followed by calcination to produce the binder is expensive. However, magnesium silicate rocks, such as serpentine are quite common, and there has been significant effort to react the rocks to MgO and SiO_2, using steam and high pressure CO_2. The vision is to re-cast the MgO and SiO_2 into building materials and cements. Most of these processes use a combination of high temperatures, high pressures and acids. Thus far, and potentially owing to fundamental constraints on process chemistry, the processes are not economical.

In terms of carbon abatement effect, it is important to note (a) such types of concrete store the CO_2 permanently, and (b) the natural CO_2 absorption by regular concrete over time as a reference situation. Moreover, a key driver here is the lower energy intensity and CO_2 emissions associated with production of the novel cement (relative to those of conventional cement).

7.3 Market application

In terms of applicability, there are strong parallels with concrete curing CCU. In particular, the need for these concrete products to achieve proven structural characteristics and durability. On the other hand, there a potential for concrete curing technologies to result in higher strength concrete, while reducing the time of the curing/weathering process and reduce the demand for cement – the most costly part of the concrete mix. This could potentially result in lower costs of concrete.

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[51] Huijgen, W.J.J., 2007, Carbon dioxide sequestration by mineral carbonation, Thesis, Energy research Centre of the Netherlands, The Netherlands, ISBN: 90-8504-573-8.

A recurring issue / limiting factor is the weathering of MgO cements from weak acid attack, and some products have dealt with this using insoluble coatings, such as magnesium phosphate ($Mg_3(PO4)_2$). There are a wide range of formulations of such magnesium based cements, but other than with silica and phosphate, most of these are subject to acid weathering.

The magnesium oxychloride and oxysulphate cements, known as Sorrel cements, have been developed, particularly in China, as non-structural magnesium oxychloride cements, in which the very high binder strength is traded off by using lightweight fillers. These would be a potential competitor in the non-structural arena for any novel cement.

7.4 Status quo

In terms of current market, there are strong parallels with the case for concrete curing CCU and we refer to chapter 6.

7.5 Current technology status

The current TRL for novel cements is in the range **3-6.** Most of the technology developers are still in a rather early phase and are testing at lab-scale or at the brink of realising their first pilot plant (for example, Solidia). Some companies (for instance Calera and Novacem) have faced financial difficulties.

Calera and Novacem are companies which were attempting to commercialise novel cement production technologies, in the case of Novacem relying upon magnesium-based cement technologies, though the company went bankrupt some years ago with the rights to the intellectual property developed being purchased by an Australian / UK company, Calix (Trickell & Macalister, 2012; Osowiecki, 2015). Further development is not currently being pursued.

Calix has worked on MgO cements since it was formed in 2005. Its initial commercial objective, in Australia, was to produce the binder, MgO, from the mineral magnesite in a process, now called Direct Separation, in which the process CO_2 was captured as a pure gas stream. The direct separation process was successful, and is now being applied to limestone calcination for the lime and cement industries, in the European LEILAC project. The product, MgO, produced from that process was very reactive, with a surface area >200 m^2/gm. When applied to traditional magnesium cements (see below), generally the fast hydration kinetics were not a benefit. Niche applications were developed, such as for fire resistant aerated cements. Calix found new markets for these materials, in sprayable coatings for remediating corroded concrete in sewage infrastructure, so its development of aerated and structural cements is currently not being actively pursued.

Solidia uses a patented cement that reacts with CO_2 and water to create “Solidia concrete”. The company claims a number of advantages (Riman, 2016; Soldia Technologies, 2016) including: concrete production and handling using conventional concrete manufacturing techniques, equipment and raw materials, curing taking less time than regular concrete and material characteristics / performance equal to or better than conventional concrete (compressive strength, abrasion resistance and freeze-thaw cycling resilience).

7.6 Future growth potential to 2030

The TRL for novel cements may reach **6-8** by 2030, provided that concerns about variation in long-term cement chemistry and economics have been allayed.

The deployment of novel cements requires substantial progress in terms of technology development and, in particular, the products need to achieve a proven track record and be adopted in the established body of standards and codes that the building sector relies on. This will require long-term trials and tests which, given the early stage of development of these novel cement technologies, is not expected to be feasible by 2030.

This analysis is consistent with the Cement sector's Industrial Decarbonisation and Energy Efficiency Roadmaps to 2050[52], which assumes the production of just 0.5 Mt/yr "low carbon cements" by 2050, equivalent to a 5% substitution. If it is assumed that the cements are all MgO based alternatives then this would imply a maximum theoretical utilisation of around 0.26 $MtCO_2$/yr.

7.7 Locations for deployment

It is our understanding that there are no significant deposits of magnesite in the UK (though this should be confirmed with geologists, for example the British Geological Society). Magnesite would therefore need to be imported into the UK. It is thus likely that plants would then be located near to the coast and co-located with industrial sources of CO_2, and we refer back to section 6.7 (locations for concrete curing deployment).

No specific regions have been identified, although we are aware that Solidia is interested in exploring options to enter the UK market and has been in discussion with Teesside (Riman, 2016).

7.8 Benefits and opportunities

Benefits and opportunities for novel cement are very similar to those discussed under concrete curing CCU (refer to chapter 6).

There are some such cements contending in the current Carbon XPRIZE[53] which may accelerate the technology development in the coming years.

Among the technology developers, Solidia has expressed interest in deploying their technology in the UK.

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[52] https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/416674/Cement_Report.pdf

[53] Carbon XPRIZE is a $20 Million global competition to develop breakthrough technologies that will convert CO_2 emissions from power plants and industrial facilities into valuable products like building materials, alternative fuels. See: http://carbon.xprize.org/teams

7.9 Barriers and required support

While conceptually, barriers for novel cement are very similar to those for concrete curing CCU, the following two aspects apply even more strongly than in the case of concrete curing CCU.

- It is necessary to prove that novel cement technologies lead to reliable performance and/or lower material costs for the same performance for adoption in the (conservative) building sector. As the building industry relies on an extensive body of quality standards, building codes, contractual norms and established practices. As part of this, guarantees, assurances and insurability are extremely important, in particular for structural applications.
- There is unlikely to be a strong market pull, unless the material can become more cost effective through its better strength characteristics.

For non-structural applications some requirements may be somewhat less stringent, but still relevant. Therefore, it is likely that this niche market could be among those targeted first.

8 Horticulture technology assessment

8.1 Summary

Horticulture
• **Technology outline and features:** CO_2 is added to glasshouses to enrich the growing environment. Heat is also added to extend the growing season. This study considers the use of industrial CO_2 from a source external to the glasshouse, as opposed to on-site systems. The CO_2 used in horticulture needs to be very pure to ensure that crops are not damaged. Specific pollutants that need to be controlled include NOx, SOx and ethylene. • **Applicability:** CO_2 enrichment is primarily used for tomato, cucumber, pepper and aubergine production. CO_2 enrichment is not used for other salad crops like lettuce and celery, or herbs, since these crops have a limited plant leaf area and therefore do not as readily take up CO_2. There is currently limited demand for CO_2 for soft fruit production in the UK, due to the relatively short growing season and predominant use of open-sided polytunnels. • **Status quo:** Industry stakeholders estimate that around two thirds of UK growers use on-site natural gas CHP systems, or otherwise natural gas boiler systems to supply heat and CO_2. • **Current technology status:** CO_2 enrichment in horticulture has a TRL level 9. To date, there is very limited use of industrial CO_2 in the UK (restricted to British Sugar-Cornerways and APS Salads-CF). Some growers use liquid CO_2 supplied through the bulk market, however this is an expensive option. The current industrial CO_2 demand in the UK is estimated to be around 60 ktCO_2/yr. The Netherlands is the clear market leader in applying this technology, with a utilisation of around 500 ktCO_2/yr. • **Future growth potential:** The annual industrial CO_2 demand in the UK in 2030 is estimated to range from 108–218 ktCO_2 (of which 50 ktCO_2/yr is supplied through the bulk market). The demand estimate is based on the assumption that 10% of the total planted area utilises enriched CO_2 and a CO_2 utilisation rate of 5-10% across the industry. • **Locations for deployment:** There are no specific geographical restrictions on locations, however, a key requirement is that glasshouses are located near to a reliable source of year round CO_2 and heat. Examples could include co-location of glasshouses with waste-to-energy or biomethane upgrading plants. Future projects could feasibly involve standalone sites, or nursery clusters which maximise economies of scale. Current glasshouse production is centred in East Yorkshire/Hull, Lea Valley and Thanet. • **Benefits and opportunities:** For growers, one potential benefit is that CO_2 and heat from industry may have a more stable pricing structure compared to natural gas prices. To expand the sources of CO_2 for use in horticulture, there are also opportunities to develop purification systems to clean CO_2 streams from coal, oil or biomass combustion. CCU in horticulture provides a marketing opportunity for supermarkets to promote their “green” credentials. • **Barriers and required support:** Growers that have recently installed CHP systems are likely to have no (or limited) demand for industrial CO_2. The requirement for consistent all year round, high purity CO_2 stream limits the types of industrial facilities that can supply the horticulture sector. Local authorities and regional development bodies can play an important role in facilitating the use of industrial CO_2 in horticulture. These include helping to identify opportunities for collaboration between growers and industry.

8.2 Technology outline and features

In the horticulture industry, heat is added to glasshouses to extend the growing season. In addition, for some crops, CO_2 is added to enrich the growing environment and thereby increase production yields. Typical CO_2 concentrations range between 600-1,000 ppm, compared to 400 ppm under normal atmospheric conditions.

The CO_2 used in horticulture needs to be pure to ensure that crops are not damaged. The combustion of natural gas is considered to be an ideal source of CO_2; other suitable sources of pure (or nearly pure) CO_2 include the production of ammonia, the upgrade of biogas to biomethane, fermentation and bioethanol production. Alternatively, pure CO_2 can be taken from an industrial source and directly piped into the glasshouse. Also, some growers use pure liquid CO_2 supplied through the bulk market. Flue gases from the combustion of biomass, coal and oil are not readily used as a CO_2 source for horticulture, as the impurities in the flue gases need to be removed, thereby requiring additional energy and cost[54].

Currently, the main way of meeting the CO_2 and heat requirements in horticulture is through either an on-site natural gas CHP system or a natural gas boiler. These are run during daylight hours only; the CO_2 is used directly and heat is stored as hot water in thermal tanks and released at night to warm the glasshouses. Anaerobic digestion systems have also been deployed by some growers in recent years.

The focus of this study is the use of industrial CO_2 from a source external to the glasshouse, as opposed to on-site systems.

8.3 Market application

In the UK, CO_2 enrichment is primarily used for tomato, cucumber, pepper and aubergine production. The production yield of some of these vegetables (for example, tomatoes) can be as high as 80 kg/m^2 and in some cases the vegetables can absorb up to 30% of their weight in CO_2[55]. As these products are sold on a weight-basis there is a strong driver to increase these numbers; while the horticulture industry is receptive to technologies that could boost production or lower costs.

CO_2 enrichment is not used for other salad crops like lettuce and celery, or herbs, since these crops have a limited plant leaf area and therefore do not as readily take up CO_2.

There is currently limited demand for CO_2 and heat for soft fruit production in the UK; of the demand that exists, this is mainly confined to strawberries and raspberries. The constrained demand is due to the relatively short growing season and the predominant use of open-sided polytunnels[56], rather than glasshouses, in the UK. However, the implementation of technology in soft fruit production tends to lag 5–10 years behind protected vegetable production and industry stakeholders have indicated that production is starting to move away from polytunnels to glasshouses, enabling all year round production. This will lead to a higher demand in heat and CO_2 in the coming years.

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[54] To the authors' knowledge, there is only one commercial project—SunSelect in British Colombia, Canada—that uses CO_2 from an on-site biomass boiler. CO_2 is cleaned by the ProSelect GC6 System.

[55] The horticultural industry typically expresses yields on a kg/m^2 basis. 80 kg/m^2 would equate to 800 t/ha.

[56] Elongated polythene-covered frame under which seedlings or other plants are grown outdoors.

In some cases, soft fruit production has replaced protected vegetable production; alternatively, new purpose-built glasshouses costing around £1m/ha have been commissioned.

8.4 Status quo

Natural gas-fueled CHP deployment in the horticulture industry began in the late 1990s and early 2000s; over the last decade, most growers of all sizes have opted for CHP. Currently, industry stakeholders estimate that around two thirds of UK growers use CHP systems to provide CO_2 and heat to glasshouses. Some growers also use the electricity generated by the CHP to power LED lighting to extend the growing day; otherwise, the generated electricity is typically exported to the grid. The installed CHP capacity is usually between 0.75–1 MW_{el}/ha.

The quality requirements for CO_2 are very strict, as even very low levels of impurities could damage the produce and set back many months of production[57]. Specific pollutants that need to be controlled include NOx, SOx and ethylene, which can arise during the (in-complete) combustion of fossil fuels. (Horticultural Development Board, 2009)

To date, there is very limited use of industrial CO_2 or heat sources in the UK, despite there being interest from the horticultural industry. Our understanding based on discussions with industry stakeholders is that there has been a limited willingness to engage from industrial companies. The reasons for this include that it is not core business, would take serious effort to realise and that the business case is not considered to be sufficiently attractive (while emitting CO_2 is still cheap).

Some growers use liquid CO_2 supplied through the bulk market, however this is very expensive at a cost of between £80-130/t. This is typically restricted to growers that either have a very low heat requirement (strawberries are a good example), which cannot therefore burn enough fuel to make flue gas CO_2 an option. If growers have invested in boilers that cannot produce clean CO_2, for example biomass, then liquid CO_2 can become economic, especially if they are in receipt of Renewable Heat Incentive (RHI) payments[58].

8.5 Current technology status

CO_2 enrichment in the horticulture industry is considered to be a commercially mature technology at **TRL 9**.

The CO_2 flow rate in horticulture can range from 100-300 $kgCO_2$/ha/hr; the rate used is very site specific and will vary during the year depending on the level of lighting (either natural or LED), the CO_2 demand of the specific crop, the maturity of the crop and the ventilation in the glasshouse. For example, British Sugar indicated that 200 $kgCO_2$/ha/hr is a typical flow rate for tomato production. Demand for CO_2 in glasshouses is considerably higher during the summer months.

[57] For example, a range of a concentration of 250 parts per billion of NOx can reportedly reduce tomato plant growth, and similarly exposure to concentrations of 100 to 500 parts per billion of ethylene.

[58] Personal communication with Phil Pearson, Group Development Director (APS Salads).

The current industrial CO_2 demand in the UK is estimated to be around 60 $ktCO_2/yr$. This is split as described in Table 7. There are no other known projects in the UK, although a number of projects are thought to be in development. In addition, a project was recently proposed between the Lea Valley Growers (based in the Greater London area) and Hodderston waste-to-energy plant (located 1 mile from the nurseries). Under this proposal, the Lea Valley Growers would have paid for heat and CO_2 based on metered usage. However, the waste-to-energy plant did not receive planning permission and this project was not developed further.

Table 7. Current UK CO_2 demand in the horticulture sector. (See also Appendix 3 for case studies on horticulture.)

Company	Demand ($ktCO_2/yr$)	Description
Multiple	50	Liquid CO_2 supplied via the bulk market.
British Sugar-Cornerways	5–10	CO_2 from the flue gas of the Wissington (Norfolk) sugar refinery's CHP is captured and piped into the Cornerways tomato nursery. Low grade heat is also exported. The 18 ha nursery was purpose built and is located only 500m from the sugar refinery. Cornerways is wholly owned by British Sugar.
APS Salads-CF Fertiliser	2.5-5 (estimated)	This venture is arranged between 2 separate companies located in Billingham, Teeside (originally North Bank Growers and GrowHow fertiliser plant—which were acquired by APS Salads and CF Fertiliser respectively). When APS Salads acquired the nursery, they installed two 3.3MW_{el} CHP engines to provide the CO_2 and heat supply, mainly because the CO_2 and heat supply were not sufficiently reliable due to unscheduled shutdowns at the fertiliser plant, but also to generate electricity to run LED lighting (this extends the growing day). There is a need for additional CO_2 and this is taken from the fertiliser plant, estimated to be 2.5-5 $ktCO_2/yr$.

The Global Carbon Capture and Storage Institute (GCCSI) estimated that the global annual CO_2 demand is less than 1 $MtCO_2$ (Global CCS Institute, 2011)[59]. The clear front-runner in the use of industrial CO_2 in horticulture is the Netherlands. A 2015 study published by the Dutch Ministry of Economic Affairs estimated that the current supply of external CO_2, delivered to glasshouses, either by pipeline or by truck, is approximately 500 $ktCO_2/yr$. The quantity of CO_2 delivered is not limited due to demand, but rather is constrained by the limited availability of low-cost industrial CO_2. Indeed, a 2014 study by Vermeulen (Wageningen University) estimated that the total demand in the Netherlands is between 5 and 6.3 $MtCO_2/yr$, based on a glasshouse area of 10,325 ha.

Approximately 80% of the total industrial CO_2 demand in the Netherlands is provided by OCAP CO_2 B.V.[60], a company that supplies CO_2 at a high purity level of 99% to glasshouses through a pipeline from two petrochemical sources in the Rotterdam industrial area. One of these sources is a H_2 production facility that is part of the Shell Pernis Oil Refinery; this facility emits a pure stream of CO_2 as a by-product of the H_2 production process. The other source, the Abengoa Bioenergy plant, produces CO_2 as a by-product from bioethanol production. In addition to supplying greenhouses, a further but substantially smaller part of the captured CO_2 is liquefied by Linde year-round and sold primarily to the food industry.

[59] The study does not provide the underlying assumptions used.

[60] OCAP stands for "Organic CO_2 for assimilation by plants". The OCAP concept was set by VolkerWessels and Linde Gas Benelux in 2005. In 2013, Linde took over as sole shareholder.

OCAP makes use of an existing 85 km pipeline that was used to transport oil between Rotterdam and Amsterdam, but was out of service for 25 years. The use of this transport pipeline enabled OCAP to greatly reduce the costs of the project. OCAP still had to build a distribution network of approximately 300 km of smaller pipes running to the individual greenhouses. The current OCAP infrastructure delivers approximately 400 ktCO_2/yr CO_2 to 580 greenhouses. These glasshouses cover approximately 2,000 ha production area or 20% of total national production area. According to OCAP, the re-use of 400 ktCO_2 avoids the combustion of 115 million m^3 of natural gas and avoids the emission of 205 ktCO_2/yr.[61]

In addition, WarmCO_2[62] is a project which uses residual heat and CO_2 from the Dutch Sluiskil plant of fertiliser manufacturer Yara. Heat and CO_2 is piped to vegetable growers in the nearby Terneuzen commercial greenhouse project using infrastructure supplied by partner company Visser & Smit Hanab. As a result of the Terneuzen greenhouse project, the redistribution of heat and CO_2 from Yara via WarmCO2 will reportedly result in avoided combustion of some 52 million m^3 of natural gas, which translates into a 90% reduction in fossil fuel consumption. This makes Terneuzen one of the most sustainable commercial greenhouse developments in the Netherlands. In addition, CO_2 is produced for the soft drink industry and breweries.

In the near future, supply of CO_2 is expected to grow in the Netherlands. In 2018, the AVR waste-to-energy plant in Duiven is expected to capture 50-70 ktCO_2/yr and supply companies in the Arnhem region. According to AVR, this is the first project of its kind globally. AVR also wants to capture CO_2 from Rozenburg to deliver to glasshouses in the Westland region of the Netherlands at a later date.

Outside of the Netherlands, a notable application of industrial CO_2 use in horticulture facility is the Truly Green nursery, which is co-located with the GreenField ethanol plant in Ontario Canada. The nursery covers 9 ha, with plans to increase to 36 ha over 10 years. The ethanol plant supplies CO_2 and waste heat to the nursery. The annual CO_2 demand used is not specified.

8.6 Future growth potential

The annual industrial CO_2 demand in the UK in 2030 is estimated to range from **108–218 ktCO_2**. This estimate is based on the assumptions on total planted areas summarised in Table 8. The planted areas are based on 2015 data[63] and assume that between 10 and 20% of the current soft fruit planted area moves from polytunnel to glasshouse production by 2030. A flow rate of 200 kgCO_2/ha/hr (or 876 tCO_2/ha/yr based on 12 hours per day and 365 days per year) was applied. The demand estimate is based on the assumption that 5-10% of the total planted area utilises enriched industrial CO_2. In addition, it is assumed that around 50 ktCO_2/yr is supplied separately through the bulk market.

[61] http://www.ocap.nl/files/Ocap_Factsheet2012_UK.pdf; http://www.the-linde-group.com/en/clean_technology/clean_technology_portfolio/co2_applications/greenhouse_supply/index.html

[62] http://www.warmco.nl/index.php

[63] Defra Horticultural statistics 2015, available at: https://www.gov.uk/government/statistics/horticulture-statistics-2015

Table 8. Estimated UK planted glasshouse area in 2030 for selected crops used as the basis for the calculation of CO_2 demand in 2030.

Produce category	Crop	Glasshouse area (ha) - LOW	Glasshouse area (ha) - HIGH
Protected vegetables	**Sub-total**	**484**	**484**
	Tomato	232	232
	Cucumber	100	100
	Sweet peppers	90	90
	Others	62	62
Glasshouse soft fruit (current)	**Sub-total**	**225**	**225**
Glasshouse soft fruit (new)	**Sub-total**	**605**	**1,210**
	Strawberry	451	902
	Raspberry	154	308
Total		**1,314**	**1,919**

There are prospects for growth of the UK horticulture sector to 2030. This can be realised through investments to intensify production to maximise crop yields in existing glasshouses and/or in the commissioning of new nurseries. An example of the former is the installation of LED lighting by growers that are looking to maximise production by extending the growing day—this development will increase CO_2 demand but also electricity use and consequently indirect CO_2 emissions. However, horticulture is a very competitive sector, with production from Spain and the Netherlands posing challenges to growth of the UK sector.

Globally, the GCCSI (2011) estimated that the annual CO_2 demand for horticulture in 2030 will range between 1–5 $MtCO_2$.[64] A 2014 study by Vermeulen (Wageningen University) estimated that the range of the total annual CO_2 demand in the Netherlands over the next 10 years will range between 2.6-10 $MtCO_2$ based on a glasshouse area of 10,325 ha, compared to the current usage of 5-6.3 $MtCO_2$/yr. This estimate includes CO_2 from both onsite generation and industrial sources.

In terms of carbon abatement, the utilisation of captured CO_2 in horticulture has the potential to avoid substantial quantities of CO_2 emissions from natural gas combustion in glasshouses. Potential challenges to its full deployment include the strict CO_2 purity requirements and the transportation distance. LCA is needed to ensure that carbon abatement occurs through CO_2 use in glasshouses, taking into account the avoided emissions, but also the energy used for compression and transportation. Furthermore, around 80% of the CO_2 utilised is vented with fresh air intake to control humidity. This means that (were CCS infrastructure to be developed) for any CO_2 used in horticulture, 90% storage of CO_2 would be replaced by ~ 88% release of CO_2 (i.e. 10% not captured at the source, 80% of that used for horticulture is vented).

[64] Underlying assumptions to this estimation have not been provided.

8.7 Locations for deployment

There are no specific geographical restrictions on the locations where enriched CO_2 can be used in the horticulture industry. However, a key requirement is that glasshouses are located near to a reliable source of year round CO_2 and heat. Vermeulen (2014) indicates that a distance less than 10 km for the CO_2 and 5 km for heat is ideal, however this will vary with the scale of the horticulture cluster provided with CO_2. Examples of suitable systems could include co-location of glasshouses with waste-to-energy or biomethane plants. A further requirement is that there is sufficient land availability close to the sources of heat and CO_2 (horticulture projects are typically several hectares in size). In addition, the land must be flat, to allow glasshouses to be built.

Future projects could feasibly involve standalone sites, or nursery clusters which maximise economies of scale. Transportation to the bigger clusters could take the form of pipelines over some distance, complemented by truck transportation. The location of future projects could include growers located in East Yorkshire/Hull area, Lea Valley and Thanet regions, with existing nurseries replacing CO_2 produced by end-of life CHP or boilers with industrial CO_2 or using industrial CO_2 as a 'top up' (see Figure 6 for details of existing locations of glasshouses in the UK). Alternatively, newly built nurseries are also potential sources of demand. A further factor is that nurseries need to have access to a distribution network to transport produce to market.

One of the key hurdles to development of industrial CO_2 use in the horticulture sector is the lack of competition in the CO_2 market. Many CO_2 sources are either freely emitting, or have little interest in capturing and transporting CO_2 due to its non-core business nature. Companies that do currently capture and sell CO_2 to the horticulture sector set a CO_2 price that they believe will be accepted by horticulture (typically one which is only marginally cheaper than the CHP alternative).

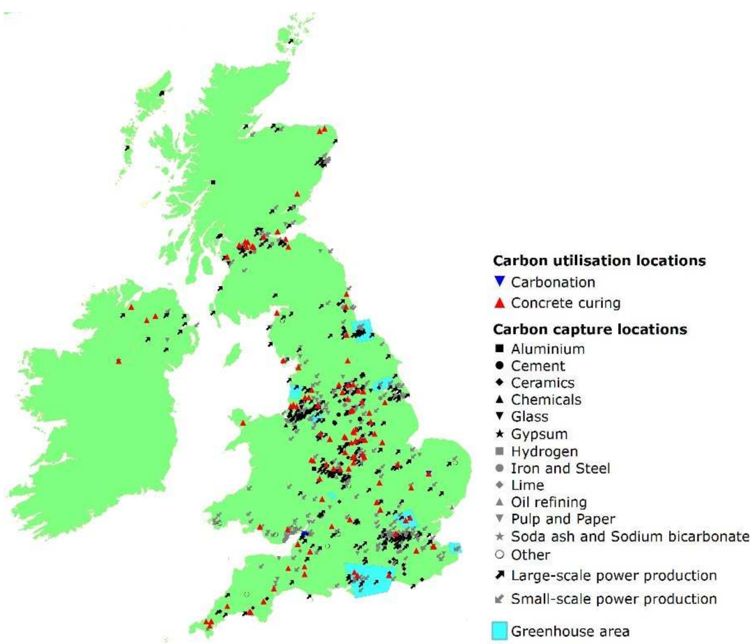

Figure 6. Map showing emission sources and the main locations of the glasshouses in the UK (shaded in green). A full-page map is included in Appendix 4.

8.8 Benefits and opportunities

Potential gains from industrial CO_2 use in the horticulture sector can be realised by both growers and industrial plants as well as broader environmental benefits. For growers, one potential benefit is that CO_2 and heat from industry may have a more stable pricing structure compared to natural gas prices. For example, waste-to-energy plants, which are not covered under the EU Emissions Trading Scheme (ETS), could supply CO_2 at a competitive price to growers on long-term contracts. This would also provide waste-to-energy plants with an additional revenue stream. In addition, CO_2 use in horticulture can serve as an enabler in land-use intensification, resulting in lower overall environmental impacts from production.

Diverse opportunities on this application of CCU can be identified. Importantly, horticulture can play a supporting role in CCU development at both cluster-level, by increasing demand for CO_2 and sharing the capture and transport infrastructure, as well as on the stand-alone project level. Also, industrial CO_2 use in horticulture is an opportunity to utilise food-grade CO_2 captured during the upgrading of biogas to biomethane, which would otherwise not be used by the beverage industry for carbonation. This is reported to occur if the feedstock used to produce the biogas is a waste. Furthermore, CCU in horticulture provides a marketing opportunity for supermarkets to promote their “green” credentials.

Finally, to expand the sources of CO_2 for use in horticulture, there are also opportunities to develop purification systems to clean CO_2 streams from coal, oil or biomass combustion. Currently, limited options are available to the market.

8.9 Barriers and required support

Several demand-side barriers to the growth of this application of CCU can be identified. Firstly, growers that have recently installed CHP systems are likely to have no (or limited) demand for industrial CO_2. However, opportunities do exist for those growers that are due to replace older CHP systems or boilers. Another barrier is that existing growers are unlikely to relocate to be close to sources of industrial CO_2 and heat. Even for new glasshouses, there may be a barrier to locating near to sources of industrial CO_2, as these locations are likely to be zoned as industrial land and therefore command substantially higher land prices are demanded than agricultural land. Furthermore, a minimum scale of the (cluster of) glasshouses will be required, depending on the transportation distance, to warrant the investment in CO_2 capture and transportation infrastructure required. Finally, currently CO_2 is used inefficiently (as discussed in section 8.6), therefore, very careful consequential LCA is required prior to promoting this technology.

On the supply side, the requirement for consistent all year round, high purity CO_2 stream limits the types of industrial facilities that can supply the horticulture sector. Temporary plant outages would necessitate more expensive bulk CO_2 purchases from growers. There is also currently limited industry interest in investing in CCU to supply the horticulture market as this is seen as non-core business and a risky endeavour.

Finally, there is also a barrier to this application of CCU as projects between separate companies are more difficult to advance, compared to ventures between the same company (or companies that have a commercial stake in the nursery). APS Salads have reportedly tried to initiate projects with several industrial companies over the years, without success (the Billingham venture was set up North Bank Growers).

Local authorities and regional development bodies can play an important role in facilitating the use of industrial CO_2 in horticulture provided this application can demonstrate actual realisable CO_2 emission benefits. These include setting up initiatives to bring relevant stakeholders together and to help to identify opportunities for collaboration between growers and industry, providing funding to conduct feasibility and, critically, LCA studies, and also placing planning conditions on developers of new commercial/industrial developments to explore options to use waste CO_2 (and heat). Furthermore, local and national government could provide incentives such as corporate tax reductions for the co-location of new glasshouse production with an industrial CO_2 source.

9 Polymer processing technology assessment

9.1 Summary

Polymer processing

- **Technology outline and features:** The technology involves combining CO_2 with relatively reactive species (epoxides) such as propylene oxide to produce polycarbonate polyols (the lead candidate being polypropylene carbonate). The uptake can feasibly range between 15 and 50% depending on the process and the application for which polyol will be used. The attractiveness of this process is fourfold: 1. it locks up CO_2 in relatively stable materials; 2. it substitutes fossil-based inputs; 3. it produces materials which can directly substitute similar polymers; and 4. it has the potential to be economically attractive without subsidies.
- **Market application:** The technology is readily applicable in the sense that the materials produced are direct substitutes of large scale polymers already available in the market, in particular precursors for polyurethane production.
- **Status quo:** The core breakthroughs have been in the area of catalysis which enables the production of polycarbonate polyols. A particular feature is the target of being able to use existing polymer production facilities with these new processes with minimal retrofit.
- **Current technology status:** The technology is at TRL level 8. A number of companies (UK: Econic Technologies; Overseas: Covestro, Novomer, Norner, Empower) are at the pilot or demonstration plant stage and showing promise. Novomer (recently purchased by Saudi Aramco) is due to start full scale plant production in 2019.
- **Future growth potential:** This is a technology with good growth potential given its direct applicability to existing supply chains (polyurethanes – global demand of 16.5 Mt/yr), leading to an estimated CO_2 demand in the UK of up to 100 ktCO_2/yr. This assumes the deployment of up to 2 commercial scale plants, each with a capacity of 100 kt/yr capacity and a 50% CO_2 uptake.
- **Opportunities and barriers:** The opportunity lies strongly in the economic rationale for producing these products which in principle should be lower cost and lower carbon than their fossil derived counterparts. The barriers are primarily around scaling up and proving the technology in the UK.
- **Locations for deployment:** Obvious locations for deployment are those with significant CO_2 emissions and petrochemical clusters, particularly those that handle similar materials to the required precursors. Examples include Teesside, Grangemouth and Fawley/Hythe.
- **Benefits and opportunities:** The technology can facilitate the development of CCS infrastructure around the chemical industry, bring potential economic gains over traditional polyols and utilise redundant capacity at existing industrial sites.
- **Barriers and required support:** A key barrier is the lack of plants (even at large pilot scale) producing the polymers in the UK. Targeted support, for example through a demonstration competition, could help to further commercialise the technology and accelerate its deployment in the UK. A second barrier is the risk averseness around new products, i.e. confidence for users of polycarbonates (e.g. polyurethane manufacturers) that the material will perform as expected. Given that polyurethane formulations have been designed with polyether polyols there is also a useful role for policy support in R&D and scale up in material design and testing.

9.2 Technology outline and features

Since 1960, a lot of research has been undertaken to develop catalysts that convert CO_2 into useful chemical intermediates, such as polycarbonates and other polyols. One of the major challenges is that CO_2 is a very stable molecule and exists in a low energy state. A sophisticated catalyst and effective co-reagent is therefore needed that would enable the use of CO_2, with minimum energy requirements. Some commercially viable catalysts have been recently developed that enable the incorporation of CO_2 into polymer production processes. A number of co-polymers can be synthesised by the co-polymerisation of CO_2 and highly reactive molecules (because CO_2 is not reactive in itself). The most widely researched is the co-polymerisation of epoxides to make polycarbonates[65].

This new approach to producing polymers and high value chemicals uses CO_2 as a feedstock. The technology transforms CO_2 into polycarbonates such as **polypropylene carbonate** (PPC) and **polyethylene carbonate** (PEC), using catalysts in a reaction with an epoxide (propylene oxide (PO) and ethylene oxide (EO)) molecules. The production of **polycyclohexene carbonate** (PCHC) with cyclohexene oxide as the epoxide is also being explored[66].

For illustration, the reaction of CO_2 with PO to make PPC can be conceptualised as the following chemical process:

$$n\,(CH_3CHCH_2O) + n\,(CO_2) \rightarrow \mathbf{(CH_3CHCH_2CO_3)_n}$$

In other words, *n* moles[67] of PO (CH_3CHCH_2O) reacts with *n* moles of CO_2 to produce a PPC molecule with degree of polymerisation *n* (i.e. n repeating units of monomer).

Co-polymerisation traditionally takes place under high pressure and temperature, but recent developments have led to the formulation of catalyst routes that can operate under low pressure (5-10 atmospheres) and at ambient temperatures[68]. The polymers produced have different properties - hard, soft, transparent, opaque- based on the epoxide used and can contain up to 50% CO_2 content by weight. The energy requirement in the conversion process is approximately the same as with traditional petroleum based feedstock. One major difference is in terms of carbon abatement through the replacement of epoxide with CO_2. Furthermore, as epoxides are toxic chemicals their displacement, therefore, has other environmental benefits[69].

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[65] http://www.econic-technologies.com/wp-content/uploads/2013/09/PU-Magazine-Aug-Sept-edition-13.pdf

[66] Econic Technologies and Empower Materials are both active in this area: see: http://www.tuvnel.com/_x90lbm/2-Econic_Technologies.pdf and http://www.empowermaterials.com/products

[67] The mole is the unit of measurement in the International System of Units (SI) for amount of substance. It is defined as the amount of a chemical substance that contains as many elementary entities, e.g., atoms, molecules, ions, electrons, or photons, as there are atoms in 12 grams of carbon-12 (12C), the isotope of carbon with relative atomic mass 12 by definition.

[68] http://www.econic-technologies.com/wp-content/uploads/2013/09/PU-Magazine-Aug-Sept-edition-13.pdf

[69] https://www.cdc.gov/niosh/idlh/75218.html

9.3 Market application

CO_2-based polymers can be engineered as thermoplastic materials[70] which can be used in numerous applications. **Polypropylene carbonate** (PPC) can be used to increase the toughness of epoxy resins and is also incorporated as a sacrificial binder in the ceramic industry, although its main use is likely to be in the production of polyurethanes. PPC also finds its applications in enhanced oil recovery (PPC surfactants, together with supercritical CO_2, can be pumped into oil reservoirs which improve the solubility of CO_2 thereby increasing oil recovery), coatings (protective coatings on furniture, flooring, electronic appliances, automotive spare parts, etc.), packaging (because of their impact resistance, stiffness and oxygen barrier protection, they can be used in many packaging applications like blow moulding, inject moulding, etc.) (Global CCS Institute, 2011). **Polyethylene carbonates** (PEC) can be used as plasticisers to increase plasticity or viscosity of different materials**.** PEC also finds applications in food packaging by acting as a barrier to oxygen thus preventing food spoilage (Global CCS Institute, 2011).

These CO_2-based polymers could potentially replace conventional polymeric polyols like polyether and polyester polyols (made by catalysed addition of epoxides like ethylene or propylene oxide with monomeric polyols such as glycerine, ethylene glycol, sucrose, etc.) in their end-use. These polymeric polyols are usually used to produce other polymers, for instance they are reacted with polyisocyanates like **methylene diphenyl diisocyanate** (MDI) or **toluene diisocyanate** (TDI) to produce **polyurethanes**. Depending on the pairing of polyisocyanates with polyols and the reaction conditions, polyurethanes can be adjusted for their characteristics such as flexibility, rigidity, abrasion, tear resistance, tensile strength, load-bearing ability, chemical resistance and electrical properties.

There are no clear indications that polycarbonate polymers will be superior to the existing petrochemical based polymers. During the 5 December 2016 workshop, a participant indicated that there is a possibility that polymers with better functionalities could be designed. In the expert opinion of Imperial college London, CO_2-based polyols appear to have similar functionality and potentially lower cost for polyurethane applications. Based on a high level analysis, Imperial College London estimate that CO_2-based polymers are between 15-30% cheaper than the standard polyether polyol made from PO (see section 9.4).

According to Imperial College London the first target market application for CO_2-based polymers is also the polyurethane market where they can be incorporated into various product formulations (i.e. there is not a single type of polyurethane, but almost an infinite variety that can be produced according to different recipes and targeting different user requirements). Polyurethanes are versatile materials which can be converted into various forms such as thermosetting plastics, thermoplastics and synthetic rubber (elastomer). Polyurethanes are used in flexible foams, rigid foams, coatings, adhesives, sealants and elastomers. The industries these products cover include furniture and bedding, construction and buildings, automotive and footwear sectors.

CO_2-based polymers may also find applications as solvents, for example, PPC and PEC can be used as a solvent to obtain alkali metals from their chlorides and other salts by performing electrolysis. They can also be used as high permittivity component of electrolytes used in lithium batteries (although this will not be a high volume application).

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[70] A thermoplastic is a plastic material (typically a polymer), that becomes pliable or moldable above a specific temperature and solidifies upon cooling. Thermoplastic materials can be cooled and heated several times without any change in their chemistry or mechanical properties.

Of polymeric polyols, polyether polyols account for 90% use in industry and the rest is polyester polyols. In the expert view of Imperial College London, in the long-term a company might be able to produce rigid polycarbonates that may replace polymers like polypropylene (PP) and polyethylene (PE) in end-use applications, by 2030 this does not seem very likely though. It is considered that the Global CCS Institute provides a relatively optimistic opinion on the potential replacement of PP, PE, etc. (Global CCS Institute, 2011).

Other polymers include Polyvinylchloride (PVC), Polyethylene terephthalate (PET), Polystyrene (PS) etc. PE and PP represent the largest volume of polymers currently produced, more than 60% of the global polymer production in 2012. Polyethylene (PE) is a thermoplastic polymer used in packaging like plastic bags, plastic films, plastic containers and bottles, etc. Polypropylene (PP) is used in a wide variety of applications including labelling, packaging, textiles, stationery, reusable containers, laboratory equipment, automotive components, etc. Global polypropylene (PP) market demand was around 59 Mt in 2014 where as for polyethylene (PE) it was 83 Mt[71 72]. The EU demand for plastics in 2013 is reported to be 46.3 Mt, of this number PE and PP contributed 29.6% and 18.9%, respectively[73].

An important aspect worth considering is that polymers and plastics can also be produced from biogenic feedstocks, like ligno-cellulosic resources, agricultural waste, food waste, etc. These polymers are termed as bio-polymers, and if produced from residues or wastes do not compete with food production. By fermentation of these renewable sources it is possible to synthesise different intermediate substances that can be further used in the production of polymers like polyethylene (PE), polypropylene (PP), polylactic acid (PLA), polyhydroxyalkanoate (PHA) and Polyhydroxybutyrate (PHB)[74]. Polymers can also be recycled thereby reducing the demand for virgin polymers and also diverting material from landfill. These bio-based and recycled polymers may compete with polymers which use CO_2 as a feedstock for end use applications in the long-term.

According to Imperial College London, in the near to mid-term, bio-based polymers are likely to replace (parts of the use of) PE, PP, PET, etc. rather than polyols which will mainly be used in the PU market. The dynamics of the polymers market in the long run are hard to predict but towards 2030 renewable (bio-based) and green (CO_2-based) polymers are more likely to find entry into polymers market through different market applications. CO_2 based polymer processing should, therefore, be considered **as one of the possibilities to produce polymers with a lower GHG impact** because in several end use markets there are other “green” alternatives that could also be deployed.

9.4 Status quo

There are different catalysts being developed in the market that facilitate the co-polymerisation of CO_2. In some cases the technology has been applied and tested successfully in various applications. Some technology developers claim that their catalyst based technology can be used in the existing plants with a few retrofits.

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[71] https://www.grandviewresearch.com/press-release/global-synthetic-and-bio-based-polypropylene-market

[72] http://www.freedoniagroup.com/World-Polyethylene.html

[73] http://www.plasticseurope.org/documents/document/20150227150049-final_plastics_the_facts_2014_2015_260215.pdf

[74] https://www.umsicht.fraunhofer.de/content/dam/umsicht/de/dokumente/nationale-infostelle-nachhaltige-kunststoffe/bio-based-_polymers.pdf

An industry stakeholder consulted in the context of this study is of the view that for the production of low molecular polyols for further conversion to polyurethanes, existing plants can most likely be retrofitted (in some cases with fairly low levels of change required), however this will depend on the type of a catalyst and process requirements, as well as on the specific technology. For high molecular weight polycarbonates, new plants need to be constructed. However, the process most likely will consist of a set of processes known by the industry today, put together in a new setup.

The new technology potentially provides an economic advantage over traditional fossil based production method as part of the petroleum based feedstock is replaced by CO_2, which is a significantly cheaper feedstock[75]. According to Imperial College London the capital costs, labour costs and utilities don't fundamentally change with CO_2 based polyol production, which therefore results in reduced operating costs compared to conventional production[76]. For polyurethane products these polymers seem to have similar functionality and potentially lower cost.

Despite the substantial economic gains, the technology is currently not being widely used by the existing chemical and polymer industry. A key reason for this is their acceptance by the downstream companies that are purchasing the polymers for ultimate use in end-use applications. While some of the properties of CO_2-based polymers may be enhanced for many applications they are nonetheless still different, which has an impact on downstream processes. The acceptability is likely to vary between applications, and this will determine how quickly CCU polymers can be deployed in the market.

9.5 Current technology status

Currently the technology is at TRL level **8**. This means that the technology has been developed to work in its final form and under its expected conditions. So far research has mainly produced a range of polypropylene carbonate polyols (PPC) and polyethylene carbonate polyols (PEC), which can contain up to 50% CO_2 by weight. There are numerous companies actively involved in research and developing products using this technology. These include: Econic Technologies (UK); Covestro, BASF and Evonik (Germany); Novomer and Empower Materials (US); Norner (Norway); SK Innovations (South Korea). In some cases, the companies are focussing on catalyst development, while others are also developing pilot plants.

Econic Technologies

Econic technologies (UK) is a spin-off from Imperial College London, and a leading innovative company active in the development and commercialisation of novel catalyst technologies that use CO_2 as a feedstock to manufacture polycarbonate polyols. These polycarbonates are ultimately used in the polyurethane market. The concept is shown in Figure 7.

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[75] At present, the discussion around who should pay the price for CO_2 consumed in CCU technology is inconclusive. The assertion is made under the assumption that the company using CO_2 in its CCU technology will pay a price for the CO_2. However, currently the CCU industry currently falls outside the accounting scope of EU-ETS: http://www.scotproject.org/images/Briefing%20paper%20EU%20ETS%20final.pdf

[76] Assuming that raw material costs are reduced by 40%, and that these represent 60% of the product costs then the cost reduction is 24%.

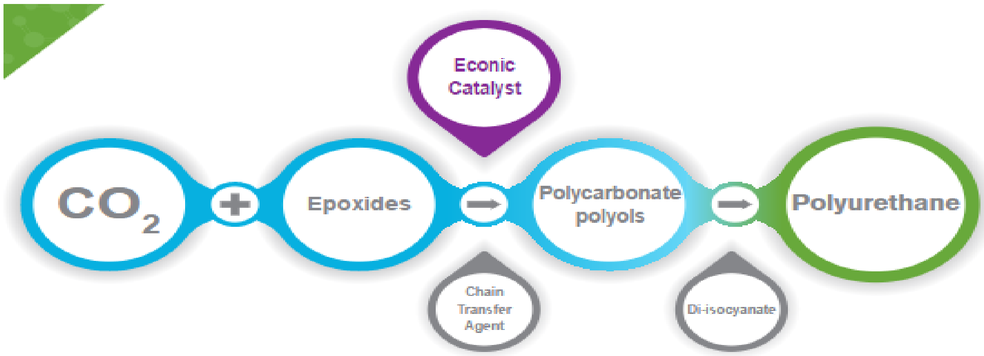

Figure 7. Overview of the production of polycarbonate polyols[77].

- Econic's catalysts operates at low pressure and temperature for the reaction between CO_2 and epoxides, creating savings for plant design and offering a safer and less exothermic production method. A lead epoxide under consideration is PO.
- The CO_2 content in the end product can range from 30-50% by weight. For every tonne of CO_2 used, an additional 2 tonnes of CO_2 are saved (avoided emissions by substituting epoxides with CO_2) thus resulting in 3 tonnes of CO_2 savings.
- The main value proposition of this technology is its economic advantage over traditional polymerisation process (as discussed in section 9.4).
- The level of purity of CO_2 (and water content) can alter the chemistry of the product in some processes. It is not necessary to use ultra-high purity grade CO_2 with Econic's catalyst – although it should be scrubbed and dried. Successful testing of the process has been undertaken in the lab using scrubbed CO_2 from the test recovery unit that was trialled at Ferrybridge power station in the UK.

In December 2013, Econic Technologies received an investment of €5.1m to further its technology testing and long-chain polymer production. The company has been also been awarded a Horizon 2020 SME grant of €2.49m to assist the commercialisation of its novel catalyst technology. The grant is likely to facilitate the demonstration of technology to potential customers enabling the acceleration of downstream product development[78].

Covestro

Covestro (Germany), a spinout formed in 2015 from Bayer Material Science, is also developing various catalysts to use CO_2 and PO to produce polyether polycarbonate polyols (PPP) suitable for use by the polyurethane industry. Both the Covestro and Econic processes follow the reaction described in section 9.2.

- The company has a pilot plant in Leverkusen, Germany which has been operating since 2011.
- In 2016, Covestro inaugurated its new CO_2-to-polyols plant in Dormagen, Germany as part of the Dream production Project and involved an investment of €15m. The construction of the plant started in 2015 and it is expected to produce 5 kt of PPP annually. The initial target market for the polyols will be the production of flexible foams for mattresses and furniture.
- The CO_2 content in the end product can range from 15-25% by weight depending upon the application for which polyol will be used.

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[77] http://www.econic-technologies.com/wp-content/uploads/2016/05/9690-EconicTec-4pg-Bro-Update.pdf

[78] http://www.econic-technologies.com/wp-content/uploads/2016/05/H2020-SME-EU-Grant.pdf

- The reaction between CO_2 and PO takes place under moderate pressure, and the resulting polyols are drop-in replacements for petroleum based polyols in a variety of commercial applications.
- The company has been doing research with leading German universities like RWTH Aachen, and with the CAT Catalytic Centre in Aachen to develop suitable catalysts for efficient reaction of CO_2 with epoxides. Covestro's Dream Production project was selected by the Danish Sustainability think tank Sustania as one of the top 100 most sustainable projects of 2016[79].

[See also Appendix 3 for a case study on Covestro.]

Novomer

US-based company Novomer, acquired by Saudi Aramco for $100m in 2016, aims to commercialise CO_2 based polymers and other chemicals. The company uses catalyst based technology to produce polymers and chemicals that contain up to 50% low cost CO_2 or carbon monoxide (CO) - so called Converge polyol technology (see Figure 8).

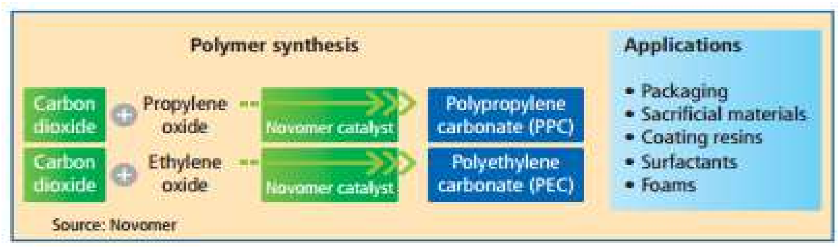

Figure 8. Overview of Novomer's process for synthesis of polycarbonates.

- The company moved in to pilot scale development for the production of CO_2 based plastic materials with Eastman Kodak Co. at its Rochester, New York location in December 2009.
- In 2013, the company announced that it had produced 7 t of polypropylene carbonate (PPC) polyol[80]. Later, it scaled up its production by combining production with Albemarle Corporation at its Baton Rouge, Louisiana and Orangeburg, South Carolina locations.
- Novomer has a very flexible polyol technology platform. It has produced tailored PPC and PEC polyols with different molecular weights (High: 45,000 and 250,000 g/mol, Low: 500-10,000 g/mol) and hydroxyl group functionalities.
- The polyols can be used in a wide range of industrial applications including coatings, foams, adhesives, elastomers, and thermoplastic polyurethanes (TPUs).
- Novomer is planning a new production facility with 50-100 kt/year production of CO_2-based polyols, and is currently under engineering design phase. The facility is expected to be operation by 2019. The site will be located in Houston, Texas[81].

Jowat AD, a supplier of industrial adhesives based in Germany, was the first company to commercially adopt Novomer's Coverge polyols for use in polyurethane formulations. Novomer has also been working with Ford to test new foam and plastic components.

[79] https://press.covestro.com/news.nsf/id/2623BAB32E79C861C1257FCD00346D37/$File/2016-055E.pdf?open&mod=09.06.2016_12:57:41

[80] http://www.econic-technologies.com/wp-content/uploads/2013/09/PU-Magazine-Aug-Sept-edition-13.pdf

[81] http://utech-polyurethane.com/news/utech-na-2016-novomer-at-ep-stage-for-new-plant/

Norner

Norner (Norway) is active in the polymerisation of CO_2 and has been developing a number of technology concepts supported by patent applications since 2008. The company plans to form a consortium to build a small scale pilot for production of polycarbonates and further to commercialise the technology.

Norner's novel procedure makes PPC thermally stable at 200 °C for 60 minutes, thus expanding the processing window for PPC. The company has also been exploring the production and use of polycyclohexane carbonate (PCHC). The research for developing polymers using CO_2 as a raw material was supported by the Norwegian Research Council. Yara and Superfos also collaborated in this research effort. The aim was to refine process parameters and explore the applications of CO_2 based polymers considering their novel properties[82].

Empower Materials

Empower Materials (US) is producing the poly(alkylene carbonate) co-polymers line of CO_2-based polymers used in electronic ceramic binders, technical glass binders, cutting tools, metal castings, etc. The company's catalyst allows the production of a wide range of poly(alkylene carbonate). The processes allow to modify the molecular weight of polyols together with other properties like adhesion and strength. The company is producing poly(ethylene carbonate), poly(propylene carbonate), poly(propylene/cyclohexene carbonate) and poly(cyclohexene carbonate).These co-polymers are amorphous, clear, can be readily processed and have long-term mechanical stability[83].

Current demand

At present the global production of CO_2-based polycarbonate polyols is limited, in the range of a few kt/yr. Efforts are underway to develop new properties and explore additional applications in order to enhance the use of CO_2 in the technology. The traditional manufacturing route to making the "equivalent" material, polyether polyols, simply involves the polymerisation of the epoxides e.g. polymerisation of PO. Hence the CO_2 based polycarbonate polyols halve the number of moles of fossil-derived epoxide going to the polymer because every second sub-unit is CO_2 rather than epoxide.

Our understanding based on discussions with industry stakeholders is that in the UK, the domestic production of petroleum based polyols is not significant, and furthermore that there is currently no production of CO_2 based polyols. Exact numbers on polyol production in the UK are not publically available. Imperial College London estimate that around 60-80% of petroleum based polyols that are used in the manufacturing of polyurethane, are imported into the UK, primarily from Germany and the Netherlands. There are some speciality polyols and PU "system houses" (production capacity ~5-20 kt/yr) active in the formulation and production of polyurethanes using petroleum based polyols. System houses perform customised manufacturing of different PU grades for use in different industries. In the production of PU from polyols and MDI/TDI, over 90% of the mass is from base polyols. According to an industry source around 150-300 kt/yr[84] of traditional fossil based polyols are used by system houses in the UK to manufacture polyurethanes.

[82] https://www.norner.no/eng/content/download/414/3374/file/Norner%20Press%20Release%2006Feb09.pdf

[83] http://cdn.empowermaterials.com/wp-content/uploads/2014/12/EmpowerMaterialsBrochure_English.pdf

[84] EU demand for plastics in 2013 was 46.3 Mt, of which UK had a share of 7.6%. Out of 46.3 MT PU accounted for 7.4% of the plastics which equates to 3.42 Mt. Considering a proportionate percentage share for UK PU demand as for plastic demand we arrive at roughly 260 Mt of PU demand for the UK in 2013: http://www.plasticseurope.org/documents/document/20150227150049-final_plastics_the_facts_2014_2015_260215.pdf

9.6 Future growth potential to 2030

The TRL for this technology is expected to reach **9** by 2030.

Global demand

Specifically for polyurethane**,** Zion Research reported that, globally, 16.5 Mt of polyurethane was produced in 2014 which is expected to grow to 25.5 Mt in 2020, growing at a Compound Annual Growth Rate (CAGR) of 7.5% between 2015 and 2020[85]. Transparency Market Research has assumed a relatively conservative growth rate of 5.9% from 2015 to 2023. This would translate into polyurethane production of 27.5 Mt in 2023 valued at around USD 82.9 billion[86].

In 2014, the largest product segment was flexible foams which held 35% share of the global market followed by rigid foams and coatings (see Figure 9). These three major product segments together contributed more than 70% of the global polyurethane market in 2014. Extrapolating production figures using a growth rate of 5.9% to 2030, we arrive at polyurethane production of around 41 Mt. According to one industry stakeholder, the CO_2 based polyurethane in 2030 could reach double digits (significantly above 10%) market share of the polyurethane market. Assuming 10-20% market share of CO_2 based polyurethanes, we arrive at global CO_2 demand of roughly **2-4 Mt/yr** in 2030.

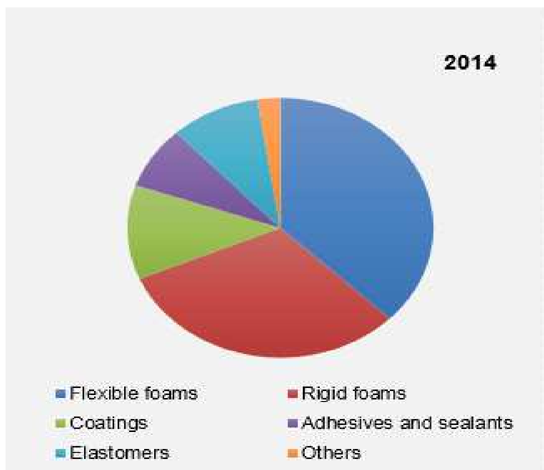

Figure 9. Global polyurethane market volume share by product segment in 2014[87].

A much bigger potential than just the PU potential would be unlocked if some of the other polymers would be replaced by CO_2 based polymers as well, like PP, PE, PVC, etc., but this comes with significant challenges. Combined production of PE and PP in 2014 was 142 Mt; assuming that demand for PP and PE increases annually by 5% until 2030[88] then this would result in around 310 Mt/yr production.

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85 http://www.marketresearchstore.com/news/global-polyurethane-market-164

86 http://www.transparencymarketresearch.com/pressrelease/polyols-market.htm

87 Ibid

88 Polyethylene (PE) is also anticipated to see a growth rate of 4.9% from 2015 to 2022: https://globenewswire.com/news-release/2016/05/17/840601/0/en/Alpha-Olefins-Market-To-Exhibit-4-2-CAGR-From-2015-to-2022-Owing-To-Increased-Demand-In-Automotive-And-Consumer-Goods-Industries-Grand-View-Research-Inc.html whereas polypropylene (PP) is expected to show a growth rate of 5.2% in the same

In our view, bio-based polymers are likely to contain relatively better share of the polymers market by 2030 compared to CO_2 based polymers, because they start from an existing base industry that is more mature (e.g. polylactic acid - PLA capacity is expected to be 800 kt/yr by 2020[89]) and bio-polyethylene capacity was over 400 kt/yr in 2013[90], while CO_2 based polymers are still in their infancy. Nonetheless, we estimate that up to 10% of conventional polymer production *could be* replaced by CO_2-based polymers by 2030, which would imply a production of PPC and PEC of 30 Mt, equivalent to **15 MtCO$_2$** used (assuming 50% CO_2 replacement). An additional demand may arise from applications of polycarbonate polyols as solvents and in lithium battery electrodes. However, the global CO_2 demand is highly uncertain in polymer processing and by 2030 could well range between **2-19 Mt**.

UK demand

The CO_2 demand for polycarbonate polyols could feasibly range between **0-100 ktCO$_2$/yr** in the UK through to 2030. This equates to up to 2 commercial scale plants, each with a production capacity of around 100 ktCO$_2$/y of PEC or PPC (i.e. a total capacity of 200 ktCO$_2$/yr) and a CO_2 uptake of up to 50%.

The demand for polyurethane tends to scale up by GDP share. The UK's Purchasing Power Parity (PPP) share of global GDP demand was 2.36% in 2014[91]. Applying the same percentage share for the UK polyurethane market from global polyurethane demand of 16.5 Mt, we estimate approximately 390 kt of polyurethane demand in the UK in 2014. Assuming similar growth rate for UK polyurethane demand as global polyurethane demand (CAGR of 5.9%) this equates to approximately 1,000 kt of PU in 2030. The reason for the higher than GDP growth rate of PU is partly driven by the need for improved quality of insulation in construction through regulation and the expected growth in building retrofits. Imperial College London's expert opinion is that it is possible that around 80% (160 kt) CO_2 base polyols are used in polyurethane formations while the other 20% (40 kt) may replace some of the traditional polymers like PE and PP in their end use applications.

This implies that around 15% (160/1,000 kt) of the UK polyurethane demand would be met through this route by 2030. The estimates from (Element Energy, 2014) provide a range of **5-150 ktCO$_2$/yr** demand in the UK through polycarbonates, which are close enough in function to polyether polyols to be considered replacements.

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period: http://www.abnewswire.com/pressreleases/synthetic-and-biobased-polypropylene-market-demand-is-expected-to-reach-8735-million-tons-growing-at-a-cagr-of-52-from-2015-to-2022-grand-view-research-inc_71098.html

It is hard to precisely predict the growth rates through to 2030. We have assumed a 5% CAGR for both PE and PP to arrive at a reference figure for CO_2 demand in 2030.

[89] http://www.bioplasticsmagazine.com/en/news/meldungen/PLA_Growth.php

[90] http://iea-etsap.org/E-TechDS/PDF/I13IR_Bioethy_MB_Jan2013_final_GSOK.pdf

[91] http://statisticstimes.com/economy/world-gdp-ranking-ppp.php

9.7 Locations for deployment

There are no existing facilities in the UK producing CO_2-based polyols. Some key aspects should be considered to identify potential future locations:

- Existing production streams and assets with synergetic links to the production processes of CO_2-based polyols:
    - Presence of necessary logistics infrastructure combined with cheap land availability or the possibility of converting existing redundant facilities to production units for CO_2-based polyols.
    - Proximity to industrial cluster with large number of companies operating in the chemical sector to provide opportunities for industrial symbiosis. But this does not exclude the possibility of using standalone sites if CO_2 sources and other raw materials are available.
- The availability of CO_2 source with a quality range compatible for use in polyol production. With Econic's technology, the CO_2 reportedly does not need to be very high quality (e.g. CO_2 from coal power plants can be used if first scrubbed and dried).

Three example locations in the UK meeting these criteria include:

- The Tees Valley Process Industry Cluster contains 58% of the UK chemicals industry and produces around 20 $MtCO_2$/yr (Armstrong, Styring, & Wilson, 2016)
    - Closure of facilities on the Wilton International site has left some redundant capacity in effluent infrastructure (Armstrong, Styring, & Wilson, 2016) Huntsman, Sabic UK petrochemicals and Lotte Chemical UK are located in the area.
    - The industry in the Teesside area is facing the challenge of de-carbonising while remaining profitable. Investments in CCS network in the region together with deployment of CCU technologies in the near term can help reduce the carbon footprint of the area.
- Grangemouth: A location with a large refinery and petrochemical complex and experience of epoxide production and where investment has taken place to receive shale gas based hydrocarbons for cracking; there are significant CO_2 emissions on site.
- Fawley and Hythe: A location similar to Grangemouth with propylene manufacturing[92] and a history of epoxide manufacturing; there are significant CO_2 emissions on site.

9.8 Benefits and opportunities

Benefits and opportunities that incentivise the deployment of this technology are listed below:

- The technology can facilitate the development of CCS infrastructure around the chemical industry in the UK which is currently responsible for a significant share of UK GHG emissions. The deployment of CCU technology could contribute to reducing emissions: some 3 tonnes of CO_2 for every tonne of fossil-based epoxide replaced. Considering the estimated UK demand of CO_2 from polymers (0-100 $ktCO_2$/yr by 2030), deployment of this technology could potentially reduce emissions by some 300 $ktCO_2$/yr by 2030. Therefore, the technology is expected to provide opportunities for industrial symbiosis and contribute to overall emission savings in the industry.

[92] http://www.exxonmobil.co.uk/UK-English/about_what_chemicals_fawley.aspx

- The CCU technology brings potential economic gains over traditional polyols enabling the industry to reduce costs and increase their profit margins in cases where the properties of CO_2 based polymers are at least similar to traditional polymers they replace.
- The CCU technology can reduce the imports of petroleum based polyols that act as a precursor to polyurethane formulations. It can only happen once the existing companies with manufacturing facilities in the UK use the catalyst technology realising its economic and environmental benefits.
- Redundant capacity at existing industrial sites can be used to start manufacturing of CO_2-based polymers (there is considerable spare/mothballed capacity in the UK). Thus, traditional chemical industry infrastructure can be used which offers an opportunity for efficient use of industrial space, avoiding unnecessary infrastructure expansion.

In adition, the UK has a strong catalytic science base and excellent underpinning research and technology in this field which it could build up if action is quick.

9.9 Barriers and required support

Polymer processing face numerous barriers to their deployment:

- There is no existing facility in the UK at the moment that is using the catalyst technology for producing CO_2 based polymers.
- Cost savings alone are not necessarily sufficient for the polymer industry to mitigate the potential risk of adopting the new technology. There are several reasons for this including, importantly, their acceptance by companies that are purchasing the polymers to use in end-use applications. While some of the properties of CO_2-based polymers may be enhanced for many applications they are nonetheless still different, which has an impact on downstream processes. The acceptability is likely to vary between applications, and this will determine how quickly CCU polymers can be deployed in the market. Polyurethane recipes have been optimised for polyether polyols inputs and these will need to be revised somewhat for polycarbonate polyol inputs.
- The source of CO_2 and its quality could necessitate additional purification at the point of source, resulting in increased costs (Global CCS Institute, 2011).
- The chemical companies in the UK do not have the catalyst technology needed to produce CO_2 based polymers, although this could be licensed.
- The technology offers non-permanent storage of CO_2, so CO_2 savings can be temporary, albeit relatively long-lived (years). In terms of contribution to achieving climate targets, the role of the technology will depend on the product life and its end of life management strategy.

In terms of technology support:

- Technology needs to be de-risked at pilot scale. A possible way to do this would be to provide developers with capital funding or grant so that they can demonstrate their technology, make samples and test their products. This would eventually allow them to attract investments for starting a commercial scale production facility or license the technology to other interested parties.

10 Synthetic methane technology assessment

10.1 Summary

Synthetic methane

- **Technology outline and features:** The catalytic hydrogenation of CO_2 to produce methane is well understood. In the context of this study, it assumes the production of H_2 via the electrolysis of water and its use to hydrogenate CO_2. Rapid response proton exchange membrane (PEM) electrolysers are best suited to this technology. Methanation can either be via a catalytic or biological process (the former requires a pure CO_2 stream, whereas the latter can utilise a dilute CO_2 stream).
- **Market application:** Synthetic methane has the same end-use applications as fossil methane. It can be used for electricity generation, for heating and cooking or as a transport fuel. It can be fed into the existing gas grid, or used directly.
- **Status quo:** Natural gas will remain important to the UK's energy mix for the foreseeable future. Total natural gas demand in 2015 was 791 TWh. Of this, 213 TWh was used for electricity production (29.5% of electricity production) and 490 TWh for final consumption (292 TWh related to domestic use).
- **Current technology status:** We consider this technology to be currently at TRL 7-8. There is no synthetic methane production in the UK at the moment. Germany has 2 operational pilot plants currently deployed as part of Germany's "Power-to-Gas" initiative. Active companies include: Audi AG, ETOGAS, Viessmann Group and Thuga Group. Denmark has 1 operational pilot plant, commissioned by Electrochaea. GRTgaz is due to commission a plant in France in 2018.
- **Future growth potential:** The attractiveness of this technology is that it, ostensibly, allows for the utilisation of increased quantities of renewable energy that would be otherwise curtailed. The business case is strongly dependent on the electolyser cost and utilisation, the price paid for electricity and the income received for any grid balancing services provided. Deployment of this technology will be reliant on a "green gas" premium to improve the business case.
- **Locations for deployment:** Any region with sufficient access to low cost CO_2 and electricity (for H_2 production) to operate the process, as well as a heat demand (the process is exothermic), and gas connection that can accept the flow produced.
- **Benefits and opportunities:** This technology provides an opportunity for the integration of intermittent renewable electricity into the existing energy system. Synthetic methane deployment has no impact on existing end-user infrastructure (e.g. gas appliances). UK company ITM Power can benefit from the deployment of synthetic methane which utilise rapid response PEM electrolysers for the production of the H_2.
- **Barriers and required support:** Barriers to deployment are the high costs associated with the synthetic methane process. Synthetic methane is strongly influenced by the annual operating hours and the electricity price. (In Germany, the price is an estimated 4-5 times the natural gas price based on current deployment.) Any support which can reduce these costs, for example with regard to electrolyser development, will greatly benefit the prospects for this technology.

10.2 Technology outline and features

Synthetic methane involves the production of methane synthesised from H_2 and CO_2. The H_2 is typically produced through the electrolysis of water, although by-product H_2 can also be utilised, if locally available. When renewable electricity is used for the electrolysis of water[93], then the methane can be considered to be a low carbon fuel.

The chemical reaction equations are indicated below:

H_2O (l) + renewable electricity → $\mathbf{H_2}$ (g) + O_2 (g)
CO_2 (g) + **4** $\mathbf{H_2}$ (g) → $\mathbf{CH_4}$ (g) + 2 H_2O (l)

This technology is also referred to as synthetic natural gas (SNG) or Power-to-Gas (PtG, P2G). It should be noted that Power-to-Gas more is typically used to describe the production of H_2 (i.e. without synthesis to methane). Similarly, the term synthetic methane is often used interchangeably with bio-substitute natural gas (bio-SNG). However, these processes are <u>not</u> the focus of this study.

<u>Electrolysis (step 1)[94]:</u>

The electrolysis of water to produce H_2 has been practised for many years and as such is a proven process. The electrolyser cost represents around half of the total investment cost of a synthetic methane plant's cost. In the 5 December 2016 workshop, it was indicated that H_2 could potentially be economically produced in small amounts. This assertion was verified by Imperial College London; the current price for H_2 at filling stations for fuel cell vehicles is around £10/kg and is projected to fall to £5/kg by 2025[95].

Rapid response proton exchange membrane (PEM) electrolysers are best suited to this technology, as they are quicker to start-up than their alternatives, offering sub-second response times, and have a wider operating window of 5–100% of nameplate capacity. PEMs also operate at high current densities so are relatively compact and are better suited to load-following sources of intermittent energy. The maximum stack capacity is limited to approximately 2 MW at present[96] PEMs, however, are at a lower TRL than their main alternative, alkaline electrolysis cells (AEC).

AECs are the most technically mature electrolyser type. They are, however, not as well-suited for intermittent operation, due to delayed reaction and difficulties in starting the system after a shut-down (process start-up can take several hours; a challenge if short-lived periods of surplus energy are to be utilised). In order to operate AECs in combination with intermittent renewable electricity sources, a wide operational range is required. Typical operational ranges are in the range of 20-100% of their nameplate capacity. Solid oxide electrolysis cells (SOEC) are a third electrolyser type, but are not yet available commercially, and are not considered to be suitable for rapid response electrolysis.

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[93] This renewable power can either be sourced via a direct connection to renewable electricity generation or from of guarantee that electricity consumed from the grid is coming from renewable sources.

[94] Power-to-gas: Climbing the technology readiness ladder: https://www.gas-for-energy.com/fileadmin/G4E/pdf_Datein/gfe2_14_fb_Grond.pdf

[95] Imperial College London analysis based on: https://www.hydrogen.energy.gov/pdfs/14004_h2_production_cost_pem_electrolysis.pdf and http://www.northerngasnetworks.co.uk/wp-content/uploads/2016/07/H21-Report-Interactive-PDF-July-2016.pdf

[96] ITM Power's current stack technology is capable of 2.2MW, but will be launching a 10-100MW stack in 2017. See: http://www.itm-power.com/news-item/100mw-electrolyser-plant-designs-to-be-launched-at-hannover

Methanation (step 2):

The reaction between CO_2 and H_2 is an exothermic reaction, producing heat, which can potentially be recovered for a useful purpose. There are two types of methanation processes, namely **catalytic methanation** and **biological methanation:**

- **Catalytic methanation** is an attractive option for its high reaction rates resulting in compact reactors. Several metals like nickel, ruthenium, rhodium and cobalt may be used as catalyst for the methanation reaction, however, nickel is usually preferred due to its high activity, good methane selectivity and low raw material price. The reaction can be carried out at temperatures of between 200-550 °C and a pressure of 1-100 bar, the wide range influenced by the catalyst used. After the reaction, heat at a temperature of between 200-550 ºC is available, offering options for process integration and waste heat usage resulting in higher process efficiency. The temperature must be controlled in order to avoid thermodynamic limitation of the reaction and catalyst degradation. Catalytic methanation has conventionally been applied at large scale and for plants operating continuously. Current research is underway to develop reactors types that are better suited to operate at small scale and intermittent operation. (Gotz, et al., 2016) (ENEA, 2016)
- **Biological methanation** is an attractive option for small plants and impure gas feeds as it operates under low pressure and low temperature (20-70 ºC) and requires rather simplified gas cleaning because of the high tolerance for impurities. Usually a micro-organism serves as a biocatalyst and the bio-process takes place in an aqueous solution where H_2 is transferred from a gas to liquid phase. Biological methanation has the potential to reduce the overall cost of methanation. (Gotz, et al., 2016) (ENEA, 2016)

Note that the production of synthetic methane is optional once renewable H_2 is produced. H_2 is a versatile chemical and could also be:

- **Converted to other gases** (such as ammonia).
- Used for many **hydrogenation reactions** in the chemical industry or in refineries.
- **Used as a fuel** (heating), using the existing gas infrastructure to be transported to locations where it is needed. The percentage of H_2 blend in natural gas limits the amount of H_2 that can be fed into the grid. The appropriate blend may vary significantly between pipeline network systems and natural gas compositions, and the percentage blend needs to be assessed on a case by case basis (Melaina, Antonia, & Penev, 2013). In the UK, the maximum H_2 blend limit is 1%, as set by the Gas Safety (Management) Regulations 1996 (GS(M)R)[97].

An example of the potential development of a H_2 based economy, is the H21 project in Leeds[98]. This explores the possibilities of producing H_2 from natural gas (by Steam Methane Reforming, in combination with CCS), and using pure H_2 as a low carbon fuel, utilising the existing natural gas network to transport H_2. This approach, however, would necessitate the wide-scale conversion (or replacement) of existing infrastructure (e.g. gas appliances, burners, compressors, piping).

[97] http://www2.nationalgrid.com/uk/industry-information/gas-transmission-system-operations/gas-quality/

[98] http://connectpa.co.uk/wp-content/uploads/2016/07/H21-Executive-Summary-Interactive-PDF-July-2016.pdf

10.3 Market application

Synthetic methane has the same end-use applications as fossil methane. It can be used for electricity generation, for heating and cooking or as a transport fuel. It can be fed into the existing gas grid, or utilised directly. Importantly, the deployment of synthetic methane enables domestic consumers to continue to use their existing gas-fired equipment (in contrast to gas grid systems run on high concentrations of H_2). Power-to-Gas technology, therefore, could enable a comprehensive integration of renewable energy sources into the overall energy system.

The deployment of synthetic methane as a transport fuel has seen particular interest in Germany to date (Audi “e-gas” initiative[99]) and is made available at selected filling stations. The heavy goods vehicle market is seen as a potential target market as commercial fleet operators are increasingly exploring options to transition away from diesel fuel to cleaner low carbon alternatives. In the UK, Waitrose has recently announced that it will operate a commercial fleet running on bio-compressed natural gas fuel[100]. Previously, the distribution division of Tesco also committed to running a fleet on bio-LNG.[101]

Synthetic methane could also be purchased by corporates seeking to decarbonise their operations. For example, Unilever recently announced that it will be using 10,000 MWh of biomethane to provide heating at 5 of its sites[102]. It is unclear whether a market premium exists for green gas at this time, and if so, what the level of premium is.

Methane is also widely used as chemical feedstock, mainly to produce syngas which can then be further converted to produce high value chemicals (such as ammonia). Methane might also be used in the production of ethylene with the methanol-to-olefins (MTO) process (methane is used to produce methanol, which is then converted to for example ethylene and propylene[103]) and with research exploring more direct routes[104].

10.4 Status quo

The **domestic production of natural gas** in the UK has been declining since 2000. The UK reached its peak natural gas production in 2000 at 107.6 billion m^3 (1,142 TWh). Since then the production has been declining at an average rate of 8% per year until 2013[105]. Total natural gas production in 2014 was 38.54 billion m^3 (409 TWh), but increased by 7.6% in 2015 to 43 billion m^3 (460 TWh). Imported gas in 2015 was 492 TWh, LNG contributed 30.28% to that amount. Total gas demand in 2015 was 74.76 billion m^3 (791 TWh = 460+492-export of 162 TWh)[106]. Of this, 213 TWh was used for electricity production (29.5% of total electricity generated)[107], 490 TWh was used for final consumption (292 TWh in the domestic sector, 94 TWh for industry and 98 TWh other final users)[108].

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[99] http://www.audi.com/corporate/en/sustainability/we-live-responsibility/product/audi-e-gas-project.html

[100] http://www.edie.net/news/6/Waitrose-showcases-biomethane-truck-fleet/

[101] http://www.lngworldnews.com/tesco-to-fuel-its-hgv-fleet-with-bio-lng-uk/

[102] https://www.unilever.co.uk/news/press-releases/2017/unilever-advances-carbon-reduction-commitment-at-five-UK-Ireland-sites.html

[103] http://www.cchem.berkeley.edu/molsim/teaching/fall2009/mto/background.html

[104] http://www.aiche.org/chenected/2013/10/single-step-methane-ethylene-process

[105] http://www.ieee.es/Galerias/fichero/OtrasPublicaciones/Internacional/2016/EIA_Energy_Country_Analyisis_UK_9mar2016.pdf

[106] https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/540923/Chapter_4_web.pdf

[107] https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/513244/Press_Notice_March_2016.pdf

[108] https://www.gov.uk/government/statistics/energy-consumption-in-the-uk

There is significant natural gas use in the UK currently, which is anticipated to continue in the foreseeable future[109], a portion of which could in principle be replaced by synthetic methane. This leads to the question of the economic attractiveness; a key consideration is whether it would be preferable to produce H_2 only.

Our understanding based on stakeholder feedback is that the price of synthetic methane in Germany is a multiple of 4 to 5 of the natural gas price based on current deployment. While we realise that the systems for electricity markets in Germany and the UK are very different, the business case for synthetic methane can be clearly understood from the following high-level analysis:

- Methane is produced from water and CO_2 (so basically by reversing burning methane, which yields water and CO_2).
- Electricity is used to provide the energy to produce methane (around 2 kWh of electricity is required to produce 1 kWh of methane).
- Electricity is typically more expensive than natural gas (per kWh), unless it is curtailed electricity or the electrolyser operator is paid to provide balancing services.
- The process requires capital expenditure ("the installation") and operational expenses (amongst others "operating and maintaining the installation").

Current deployment of this technology is therefore reliant on a "green gas" premium to improve the business case (as is the case for other green gas "drop-in" fuels). In contrast, the option of converting heating systems to use pure H_2 has been *claimed* recently to have a positive economic and carbon balance[110]. This picture would change in case of large shares of renewables deployment, without sufficient electricity balancing, which could lead to periods of low cost electricity or otherwise provide the opportunity to provide grid ancillary services. Even this would need care as the period of time over which electricity was cheap would have to be long enough to ensure effective utilisation of the electrolyser and the capital cost of the methanation technology.

Synthetic methane will need to compete against other "drop-in" green methane fuels, including **biomethane** and **bio-SNG**. A key advantage of these fuels is that their production can utilise low cost feedstocks, such as wastes or industrial residues, which positively impacts the overall business case.

Bio-SNG is produced through the thermal gasification of biomass. National Grid, in partnership with Advanced Plasma Power and Progressive Energy have been operating a £5m bio-SNG pilot plant running off municipal solid waste since 2015. Construction of a commercial facility, costing £25m, is now underway and is due to commence operation in 2018.[111] The plant is expected to produce 22 GWh/yr of gas, utilising 10 kt/yr waste. The deployment of this technology at a national level reportedly has the potential to produce up to 100 TWh/yr[112].

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[109] The Committee of Climate Change estimate a total gas demand of 760 TWh in 2030. See: https://www.theccc.org.uk/wp-content/uploads/2016/12/2016-PR-Biomethane-Technical-Note.pdf

[110] http://www.northerngasnetworks.co.uk/wp-content/uploads/2016/07/H21-Report-Interactive-PDF-July-2016.pdf

[111] http://gogreengas.com/

[112] http://blog.advancedplasmapower.com/latest-news/launch-gogreengas-biosng-pilot-plant/

According to the Anaerobic Digestion and Bioresources Association (ADBA), the UK has almost 90 **biomethane** plants in operation, an increase of 100% on the previous year[113]. Production is mainly from landfill sites, but increasingly from dedicated anaerobic digestion plants using food and farm waste and sewage. The long-term supply potential for biomethane is, however, limited by the amount of waste that can be cost-effectively accessed. The Committee on Climate Change estimates a production capacity of 20 TWh in 2030 (with no growth to 2050).[114]

10.5 Current technology status

There is no synthetic methane production in the UK at the moment.

Germany is the front runner in “Power-to-Gas” technology, with 23 Power-to-Gas plants currently operational. It is our understanding that only 2 of these plants are capable of producing synthetic methane – the remainder are producing H_2 only. Companies actively developing this technology in Germany include Audi AG, E.ON, RWE, Thuga Group and the Viesmann Group.

Audi AG operates the largest plant which is located in Wertle, Lower Saxony, Germany (see Appendix 3 for case study). This has 6.3 MW input power and the conversion efficiency from Power-to-Gas is approximately 54%. The plant receives electricity from a wind farm and has been feeding synthetic methane into the natural gas distribution network since 2013. The plant produces 1 kt/yr of methane (marketed as “Audi e-gas”) using 2.8 ktCO_2/yr. The CO_2 is obtained from an exhaust flow of a biomethane plant in the immediate vicinity which is operated by an energy utility[115]. The plant uses the **catalytic methanation** process.

Since February 2016, the Viessmann group has partnered with Audi and is producing additional synthetic gas at a pilot facility in Allendorf, Hesse. This is the first Power-to-gas plant in Germany to utilise the **biological methanation** process to produce synthetic methane at an industrial scale. In contrast to catalytic methanation, the CO_2 used in the process does not need to be present in a high concentration or purified form. As such, unrefined biomethane anaerobic digestion plants can also be used as the CO_2 source. Electrochaea has also commissioned a Power-to-Gas pilot plant (1 MW capacity) using the biological methanation process. This is located at a wastewater treatment plant near Copenhagen, Denmark[116].

In France, GRTgaz and partners are developing a 1 MW pilot plant, which will utilise both PEM and AEC electrolyser types (each of 0.5 MW capacity). The plant will either produce H_2 or synthetic methane for injection into the gas grid. It is not stated what type of methanation process will be deployed. The plant will be located near to Marseille and is due to be commissioned in 2018.[117]

Swedegas is planning to start a pilot plant in Sweden and estimate that through to 2030, 2-3 TWh of synthetic methane can be produced from Power-to-Gas in the country[118].

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[113] http://www.bioenergy-news.com/display_news/11504/number_of_uk_biomethane_plants_doubles_from_last_year/

[114] https://www.theccc.org.uk/wp-content/uploads/2016/12/2016-PR-Biomethane-Technical-Note.pdf

[115] The contractual arrangements of the CO_2 supply are not publically available.

[116] http://www.electrochaea.com/about/

[117] http://www.jupiter1000.com/en/projet.html

[118] https://www.swedegas.com/en-GB/smart_energy_systems/Power_to_Gas/Power_to_Gas_in_Sweden

There are also several companies active in electrolyser technology development. These include Hydrogenics (Canada), Proton Onsite (US), Siemens (Germany) and ITM Power (UK). ITM power, manufacturers rapid response PEM electrolyser systems that can use excess electricity to produce H_2. To date, it has supplied electrolysers to RWE's Power-to-Gas plant in Ibbenbüren North Rhine Westphalia, Germany (commissioned in 2015) and Thuga Group's Power-to-Gas plant in Frankfurt am Main, Germany (commissioned in 2013).

Synthetic methane production is likely to be mainly centred in Northern Europe including Germany, the Netherlands and Scandinavia, primarily for energy security reasons. Outside of Europe, the US is not seen as an attractive market for this technology given the abundance of (low cost) shale gas.[119]

Element Energy (2014) report a TRL for this technology at 5-7. A participant that attended the 5 December 2016 workshop remarked that this TRL wasn't a fair reflection. In particular, that the technology should not be scored a low TRL based on its current low commercial interest, as all of the component technologies are in principle commercially proven.

- Electrolysis of water to produce H_2 using PEM electrolysers is a well-developed technology (TRL level 8-9).
- The catalytic methanation reaction is well developed (Sabatier process – which is at TRL 9). However, the process has conventionally been applied at large scale and for continuous operation. Current research is underway to develop reactors types that are better suited to operate at small scale and intermittent operation.
- The biological methanation reaction is less well-developed and considered to be at TRL level 6-7.

For these reasons, and taking the German market developments into account, we consider this technology to be currently at **TRL 7-8**. We recognise that there are current commercial challenges regarding its deployment, but also note that there do not seem to be any major technical impediments to scale up.

10.6 Future growth potential

Synthetic methane offers a potential solution to utilise increased levels of renewable energy in the grid that would be otherwise curtailed. However, the technology will need to compete with other solutions that are available in the market. In the case of synthetic methane, the business case is strongly dependent on a number of factors. These include the capital cost of the electrolyser, the electolyser utilisation, the price paid for electricity and the income received for grid balancing services provided.

As such, the business case improves if electricity generation costs (from renewable sources such as wind and PV) significantly decrease, or if the share of renewable electricity from intermittent sources increases to a level which results in there being sufficient excess electricity generated during significant periods in the year which would otherwise be curtailed. In this case, the lower usage of the capital investment ("just in these moments when electricity is cheap") would be far off-set by the reduced operational costs due to the lower electricity price. Industry stakeholders consulted during this study estimate that a plant would need to run for 3,500-4,000 hours a year to be profitable.

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[119] Personal communication with Nick van Dijk (Research Director – ITM Power).

In 2016, National Grid introduced the “Demand Turn Up” grid balancing service, which enables large energy users and generators to either increase demand or reduce generation when there is excess energy and low demand on the system. In 2017, this will provide a fixed payment of between £60-75/MWh to participate in the service at specific times from 27 March to 26 October. The National Grid anticipates that a total of 3-5 GW capacity will be needed for grid balancing services in 2017, of which Demand Turn Up is one solution.[120]

According to the Renewable Energy Foundation (REF)[121], 1.1 TWh of wind power was constrained in 2016. The constraint payments totalled £81m (equivalent to an average price of £72/MWh). This represented around 1.3% of the total renewable electricity generation in 2016, or 0.3% of the total electricity generation[122]. ITM Power consider this to be a significant under representation as it only includes curtailment payments made by National Grid for wind farms connected to the high voltage transmission grid. It does not include electricity constraint for wind and solar farms that are connected to the lower voltage distribution grid.

The level of curtailment reported by the REF, although not insignificant, represents a relatively low share of the renewable electricity generation. The extent to which curtailment will increase in the period to 2030 will greatly influence the future deployment potential of synthetic methane.

In a study for DECC by Strbac et al. (2012), it was estimated that the level of curtailment in 2030 could feasibly range between 0.3-12% of renewable output, but could rise to between 20% and 30% (equivalent to between 60 and 100 TWh) by 2050 in the high renewable energy deployment pathway.

In 2013, the Centre for Alternative Energy[123] undertook modelling of a zero carbon UK energy system in 2030. The modelling estimated that in this scenario the supply of renewable electricity would exceed the direct demand for electricity 82% of the time at any one moment. Almost half of the total electricity produced (about 354 TWh/yr) is estimated to be surplus to what is directly required at the time of production. The modelling assumes that 35 GW of electrolysis units would need to be deployed, generating 126 TWh of H_2, 35% of which would be used to produce synthetic methane. This study highlights the potential impact of large-scale deployment of intermittent renewable energy sources and a potential solution of how this could be managed.

Element Energy (2014) presented **3 scenarios** for synthetic methane production in UK through to 2025. These scenarios arrive at CO_2 utilisation of 0.0002-1.8 Mt/yr CO_2. We consider that the “very high scenario” is extremely unlikely as this would require a significant level of investment in plant capacity, which given the current uncertainty around the business case remains questionable[124].

In our view, a utilisation of **9-18 ktCO_2/yr** in 2030 is a more realistic estimate. This is based on synthetic methane production of around 5-10 Mm^3/yr. The main driver to deployment initially will be to demonstrate the technology in the UK and to better understand its interplay with the electricity market.

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[120] http://www2.nationalgrid.com/UK/Services/Balancing-services/Reserve-services/Demand-Turn-Up/

[121] http://www.ref.org.uk/constraints/indextotals.php

[122] https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/513244/Press_Notice_March_2016.pdf

[123] http://zerocarbonbritain.com/images/pdfs/ZCBrtflo-res.pdf

[124] The “very high” scenario is based on a 5% substitution of the UK natural gas power generation market (on an energy basis). Equivalent to around 11 TWh (approx. 1 billion m^3) annual methane production. According to Marcus Newborough (Development Director – ITM Power), this deployment would require approximately 5.5 GW of electrolysis capacity, equivalent to an estimated £8 billion investment.

While dramatic improvements in the technology are not expected to 2030, the main driver for an improved business case would be the further development of the share (and costs) of renewables in the UK electricity mix. In this study, we didn't assess how the production of synthetic methane and its applications compare to other options that would benefit from surplus renewable electricity. This would, nevertheless be an important factor in determining whether the production of synthetic methane would stand a commercial chance in a future UK scenario with a high share of renewable electricity.

Nevertheless, we would expect developments to continue, and that by 2030 the technology will reach **TRL 8-9.**

10.7 Locations for deployment

To identify potential future locations the following aspects should be considered:

- The **availability of CO_2 sources** with a quality range compatible for use in the methanation process. Typically high quality for catalytic methanation process and less pure gas feed for biological methanation process, for instance CO_2 from an unrefined biomethane anaerobic digestion plant.
    - During the 5 December workshop, it was remarked that a good source for the CO_2 would be to capture the CO_2 from **fermentation processes** (where pure or relatively pure CO_2 is emitted when operated in anaerobic mode), as the CO_2 used would be renewable. We consider this to be a reasonable concept, although in our view this will be a niche application. Alternatively, co-location with **biomethane injection plants, bio-SNG plants** or **water treatment plants** has also been proposed by several stakeholders consulted during this study (this provides the opportunity to share gas grid injection and connection infrastructure costs). The synthetic methane would typically be injected into the low pressure gas grid in these cases.
- The CO_2 source also needs to provide CO_2 at a reliable rate so that the plant can use it when surplus electricity is available. A buffer stock of CO_2 could be otherwise be stored on-site and used as required.
- **Areas with a high deployment of (renewable) electricity** to utilise surplus electricity that would otherwise need to be curtailed. This could, for example, include a direct connection to a wind or solar farm, or a grid connection in an area with a high density of renewable energy. Alternatively, if synthetic methane plants are deployed to provide grid ancillary services (such as Demand Turn Up), then there is no specific constraint on location other than access to the electricity and gas grids. (Ultimately access to low cost electricity is fundamental to the business case for this technology.)
- Due to the high cost of transporting hydrogen, **the H_2 should be produced on site or close to the methanation plant** (Wuppertal Institute, 2015).
- **Proximity to the gas distribution network** or a large gas consumer - to benefit from existing infrastructure - and the gas grid connection / consumer should be able to receive significant volumes of gas.
- Access to a **source of potable water**. Electrolysis requires deionised water that meets specific quality requirements. (The demand for a 1MW electrolyser is ~8m^3 of water per day.) Although this is not an issue in urban areas, it may be problematic for more remote areas.

According to ITM Power, there is a good correlation geographically between the location of the gas and electricity grids, and so there are numerous potential locations to site a synthetic methane plant. Co-location with a suitable CO_2 source is considered to be more restrictive. A decentralised distributed approach is seen as the most likely market model, with the deployment of multiple smaller scale plants injecting into the low pressure grid.

10.8 Benefits and opportunities

Benefits and opportunities that incentivise the deployment of this technology are listed below:

- The technology provides an opportunity for **integration of intermittent renewable energy sources** into the existing energy system (enhancing grid flexibility).
- The production of synthetic methane from otherwise curtailed renewable electricity has the potential to serve as an **interseasonal energy storage vector** (e.g. during summer months when electricity demand is low). This provides electricity generators that deploy this technology with an alternative option to relying on curtailment payments. Furthermore, in this case the electricity utilised would effectively be "free", improving the business case.
- Natural gas, along with other energy sources like wind, solar and nuclear, plays a key role in the UK energy mix and is going to be an important fuel in the energy transition. Synthetic methane can provide an opportunity of "greening" the gas supply and reducing the UK's reliance on imported natural gas. This is only feasible if it becomes cheaper to produce synthetic methane than to import natural gas, or with a "green gas" premium. Another aspect to consider when estimating future demand for synthetic methane is the role it can play in providing **storage capacity for surplus electricity**. In this respect, synthetic methane can provide storage for longer durations compared to other storage options, such as batteries. This was highlighted in a recent report on energy storage published by the European Commission[125]. Synthetic methane could potentially be stored in underground salt caverns or aquifers in the long-term, if production volumes justified.
- The **existing gas infrastructure can be used** for storing and transporting synthetic methane. The gas can then be used for electricity production, in transportation and for heating applications in households and industry without modification to existing equipment and infrastructure.
- As such, Power-to-Gas represents a solution, not only for energy storage, but also for **decarbonising the transportation sector.**
- UK company ITM Power can benefit from the deployment of synthetic methane which utilises rapid response electrolysers for the production of the H_2.

10.9 Barriers and required support

The main barriers towards the deployment of this technology are listed below:

- **Synthetic methane cost** (around 4-5 times the cost of natural gas based on existing deployment in Germany). Synthetic methane will need to compete on cost with other green gas alternatives and also with other energy storage options. A detailed analysis was not within the scope of this study.
- There is **no existing market model** for this technology in the UK as yet. There are a number of competing options that can provide ancillary grid services. In particular, there has been significant focus on the application of battery storage to date.
- Large companies typically take a **conservative** (risk averse) approach **in adopting new technologies**. Although the technology risk for synthetic methane is relatively low, the commercial risk is high.

[125] http://ec.europa.eu/energy/sites/ener/files/documents/swd2017_61_document_travail_service_part1_v6.pdf

- **The tax regime** was cited by industry stakeholders as a barrier to the deployment of this technology. Under the current regulatory framework, synthetic methane plant operators would be treated as an end user with regard to any electricity consumed (i.e. with all taxes and final consumption levies included). An exception is if the plant is directly connected to a curtailed wind farm “behind the meter”.
- The current **limit on H_2 in the gas grid is very low** (only 0.1%). This prevents significant quantities of H_2 being injected into the grid at this time. However, we understand that this is under review and it is likely that the level will be increased in the period to 2030 (some European countries permit blending up to 12%.) Furthermore, initiatives like the H21 project are exploring options for the wide-scale conversion of natural gas supply with H_2. As such, a barrier to uptake is that Power-to-Gas technology will primarily be deployed to produce H_2 only (as is the case in Germany).
- **Lack of significant availability of surplus renewable electricity**. In 2015, the renewable electricity share in the total electricity consumption (338 TWh) was roughly 25%, equal to 83.3 TWh[126]. According to an industry stakeholder, the share of renewables in the electricity mix needs to be 80% or more for there to be sufficient surplus supply of electricity and be able to make Power-to-Gas plants profitable with annual operating hours ranging between 3,500-4,000 (based on the German market). Although the share of renewables in the UK power sector is increasing, it is not set to reach close to 80% by 2030[127].

Support to address these barriers, could consist of:

- Support could be provided for electrolyser technology development with the aim of reducing the overall cost of the technology, and ultimately the cost of producing the H_2.
- Exploring possibilities to reduce or exempt electricity consumption for synthetic methane production (or CO_2 utilisation more broadly) from taxes and levies. We are aware that Ofgem recently ran a consultation which covered this aspect in the context of electricity consumption for battery storage[128]. A consistent approach should be taken for synthetic methane to ensure that the technology is not placed at a commercial disadvantage.
- Regulatory and financial support to incentivise the adoption of this technologies such as low-interest loans or tax incentives.
- Allocation of funding for funding a demonstration plant(s) to test the application of the technology. Such expenditure could be seen in the context of national infrastructure investment. The National Grid would be well placed to manage such a project, along with active participation from other key stakeholders like Ofgem.

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[126] https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/513244/Press_Notice_March_2016.pdf

[127] https://documents.theccc.org.uk/wp-content/uploads/2015/10/Power-sector-scenarios-for-the-fifth-carbon-budget.pdf; http://www2.nationalgrid.com/uk/industry-information/future-of-energy/future-energy-scenarios/

[128] https://www.ofgem.gov.uk/system/files/docs/2016/12/smart_flexible_energy_system_a_call_for_evidence.pdf

11 Synthetic methanol technology assessment

11.1 Summary

Synthetic methane
• **Technology outline and features:** The catalytic hydrogenation of CO_2 to produce methanol is well understood. In the context of this study, it assumes the production of H_2 via the electrolysis of water (or use of by-product H_2) and its catalytic combination with CO_2. The renewability of the methanol is contingent on using renewable electricity to produce the H_2. This could be sourced directly from renewable electricity generation assets (e.g. private wire connection to a wind farm or solar farm), or using surplus renewable electricity that would otherwise be curtailed due to grid capacity constraints. The minimum CO_2 quality is 99% purity at the inlet to the reactor. • **Applicability:** Methanol is a versatile chemical used in a diverse range of applications, both as a chemical feedstock (e.g. processing into formaldehyde), or as a transport fuel (principally in blending with gasoline). • **Status quo:** Conventionally, methanol is commercially produced by natural gas reforming or gasification of coal. Current global production capacity/demand is around 110/60 Mt. • **Current technology status:** We consider this technology to be at TRL 8. There are no commercial or pilot scale synthetic methanol production plants in the UK at this time. Carbon Recycling International (Iceland), is the market leader and has operated an industrial scale plant since 2012, which after an upgrade in 2015 produces 4 kt/yr plant, utilising around 6 ktCO_2/yr. Furthermore, the company has received two grants under Horizon 2020 to develop pilot scale projects in Sweden and Germany. • **Future growth potential:** The EU transport fuel market is seen as the main potential deployment opportunity for synthetic methanol in the period to 2030. We estimate a potential CO_2 utilisation of 0-145 ktCO_2/yr in the UK, based on up to two 50 kt/yr commercial scale plants. The attractiveness of this technology is that it, ostensibly, allows for the utilisation of increased quantities of renewable energy that would be otherwise curtailed. However, the UK is not characterised by significant quantities of curtailed renewable power, nor will it be in the period to 2030. • **Benefits and opportunities:** The deployment of alternative fuels, such as synthetic methanol (or its derivatives) could potentially help companies meet more stringent (non-CO_2) emission targets for vehicles, subject to verification of engine performance. Synthetic methanol counts towards UK and EU Member State renewable transport targets. Potential opportunity for synthetic methanol deployment in shipping post 2023. • **Locations for deployment:** This technology could be applied in any region which has reliable available low cost feedstock (CO_2 and H_2) in addition to the availability of sufficient low cost energy (thermal and electrical) to operate the process in an economically viable way. • **Barriers and required support:** The technology faces a number of barriers. These include: cost (at least twice the cost of conventional methanol), restrictions on blending levels (3% in the EU), multiple competing low carbon fuel options, lack of existing methanol fuelling infrastructure and the lack of understanding of the air quality benefits of using methanol. Funding on vehicle compatibility and engine testing could help to remove some of these barriers.

11.2 Technology outline and features

Methanol can be produced by the catalytic hydrogenation of CO_2, which occurs reversibly via the following thermo-chemical reaction:

CO_2 (g) + $3H_2$ (g) ⇌ **CH_3OH** (l) + H_2O (g)

The H_2 is produced through the electrolysis of water using renewable electricity (step 1) and the CO_2 can be obtained from an industrial source. The CO_2 stream used in the process must be at least 99% pure and free of major impurities which may interact with the catalyst (e.g. sulphur compounds, reactive gases including O_2, tar and soot). CO_2 can either be sourced that already meets the quality requirement (i.e. carbon capture system that removes the impurities), or is otherwise further cleaned-up on-site (step 2). The CO_2 and H_2 are streams are mixed under pressure (step 3) and reacted in the presence of a catalyst (i.e. synthesised) to form methanol (step 4). Distillation is used to remove water that is produced during methanol synthesis (step 5). Figure 10 below provides an overview of the key inputs and production process steps involved.

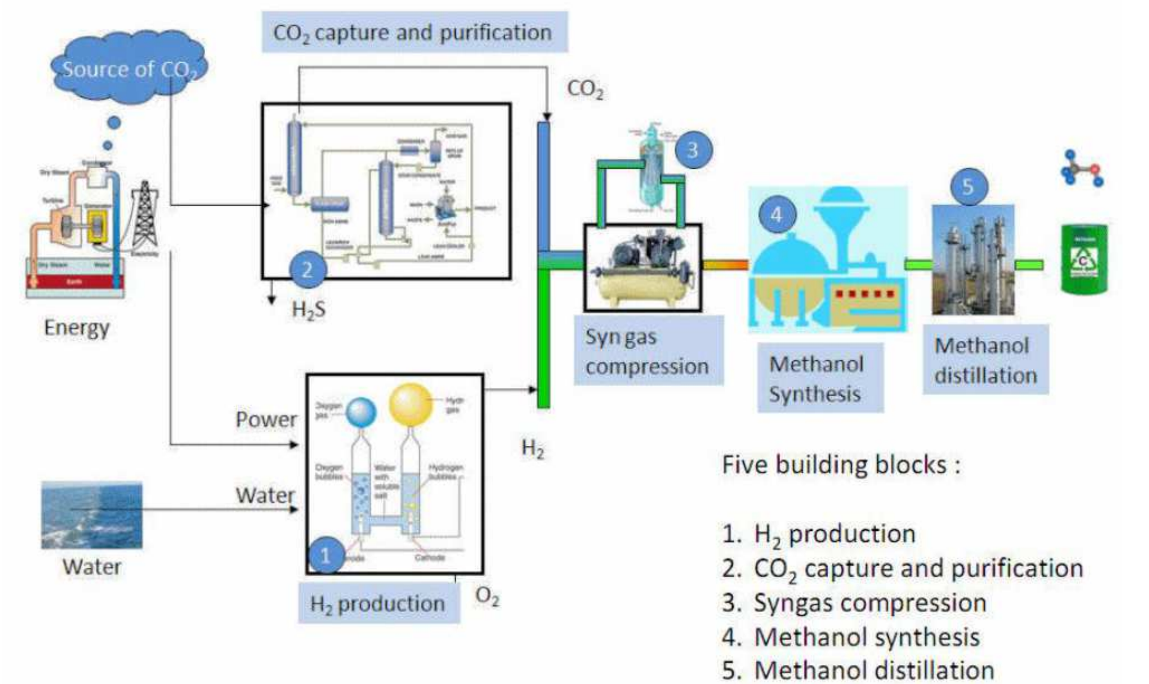

Figure 10. Schematic of the synthetic methanol production process. Note that this schematic assumes that the CO_2 source is supplied by the power generation plant. Source: (Mac Dowell and Fennell, 2015) based on Carbon Recycling International (CRI).

Methanol produced through this process can be termed "synthetic" methanol. In the context of EU renewable transport policy, synthetic methanol falls under the category "**renewable liquid and gaseous transport fuel of non-biological origin (RFNBO)**"[129], which is defined as a "*liquid or gaseous fuels other than biofuels whose energy content comes from renewable energy sources other than biomass, and which are used in transport*" and "**carbon capture and utilisation for transport purposes, if the energy source is renewable**".

The renewability of the methanol is contingent on using renewable electricity to produce the H_2, despite the fact that the CO_2 may be derived from a non-sustainable fossil source. This could be sourced directly from renewable electricity generation assets (e.g. private wire connection to a wind farm or solar farm), or using surplus renewable electricity that would otherwise be curtailed due to grid capacity constraints. In this case, it must be noted that the levelised cost of the H_2 will be substantially influenced by the availability and cost of this energy, including the not-insignificant capital cost for the electrolysers[130]. Alternatively, grid electricity could potentially be used if a guarantee of origin (GOO) is supplied along with the electricity.

By-product H_2 from other industrial processes can also be used as an alternative to electrolysis. Such sources of H_2 include chlor-alkali production and coking-gas from steel manufacturing[131], although in the latter case the H_2 needs to be purified before use. A policy consideration is how the carbon intensity of methanol produced from by-product H_2 captured from an industrial source should be calculated and verified.

There are various estimates of the energy efficiency of the process. A recent reference is the JRC study (Pérez-Fortes and Tzimas, 2016), which suggests that figures of the order of 30-40% should be achievable. In our experience this is a function of several process variables including reactor residence time (approach to equilibrium), reactor temperature (equilibrium compositions), recycle ratio and purge, degree of energy integration, catalyst performance and so forth. This contrasts with efficiencies of around 60-65% for the production of H_2.

According to Carbon Recycling International (CRI)[132], the process utilises around 1.45 t CO_2 per t methanol production. This is consistent with the academic literature which cites a CO_2 utilisation rate of 1.49 (Van-Dal E.S and Bouallou C., 2013).

11.3 Market application

Methanol is a versatile chemical used in a diverse range of applications (see Figure 11 below for an overview). The largest scale applications in terms of volume are processing into formaldehyde (29%), which is further treated to form resins, glues and various plastics, conversion to dimethyl ether (DME) through catalytic dehydration (10%) where it is used as an aerosol propellant and the production of acetic acid (9%) which is essentially used for the production of polyester fibers and polyethylene terephthalate (PET) plastics.

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[129] The terms were introduced in Directive EU 2015/1513, published on 7 September 2015 (also known as the "ILUC Directive"). Member States have until September 2017 to transpose this directive into national legislation.

[130] According to (Pérez-Fortes and Tzimas, 2016) the electrolyser represents almost 55% of the total plant investment ("ISBL" – "Inside Battery Limits" basis).

[131] Steel mill gas comprises around 44% nitrogen, 23% carbon monoxide, 21% carbon dioxide, 10% hydrogen and 2% methane. Source: https://www.thyssenkrupp.com/en/carbon2chem/

[132] Personal communication with Benedikt Stefánsson (Director of Business Development - CRI).

More recently, an emerging use for methanol is in the production of light olefins (10%) such as ethylene and propylene (methanol-to-olefins - MTO) which has seen undergone significant market growth since 2011. (The olefins are reacted to produce polyolefins used in plastics.)

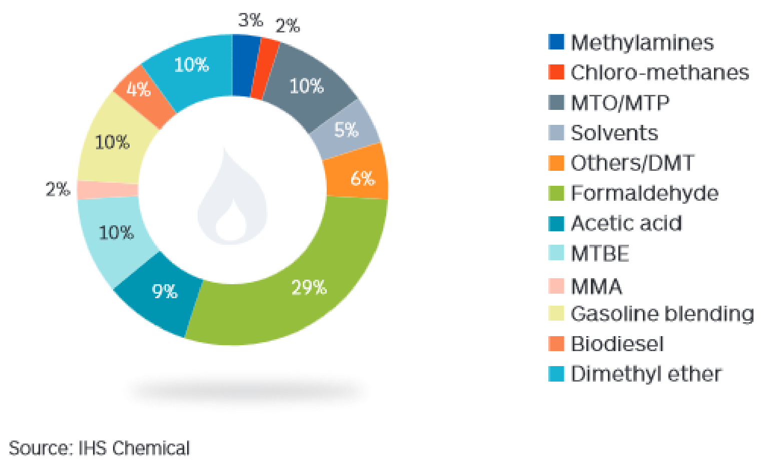

Figure 11. Overview of global methanol demand by end-use in 2015. Source: http://www.methanol.org/the-methanol-industry/

Methanol has a number of applications as a transport fuel. The principal use is in blending with gasoline (13%)[133]. In China, methanol is used as a motor fuel in various blends ranging from 5% methanol in gasoline (M5) to 100% methanol (M100) and accounts for 7-8% of China's total gasoline consumption[134]. In the EU, the EN228 fuel standard effectively restricts the methanol blend to a maximum of 3%, equivalent to an estimated demand of 1-2 Mt/yr. Similarly, methanol blending in North America is restricted. Methanol can also be used in higher blends of up to 85% methanol in gasoline (M85), but deployment is limited to special Flexible Fuel Vehicles (FFVs).

Methanol is also used as an oxygenate fuel additive in the form of methyl tert-butyl ether – MTBE (10%), but this is restricted to markets outside of the US. (It's use was prohibited by several US states due to safety concerns and since 2006 the US no longer uses MTBE[135].) Methanol is also used as a reagent in the production of biodiesel (4%). It should be noted that in the EU there is no requirement for the methanol to be of renewable origin to be counted towards Member State renewable transport targets. More recently, methanol derivatives have started to be deployed as alternative transport fuels. These include dimethyl ester (DME) and dimethoxymethane[136] (DMM/OME) as a diesel replacement in heavy-goods vehicles. Further deployment of methanol or methanol derivatives should be assessed in the context of the extent to which they could displace both conventional transport fuels, and compete with alternative low-carbon or renewable fuels. In addition, there are several barriers to deployment which may limit deployment potential (see section 11.9 below).

[133] The methanol is either blended directly with gasoline or in combination with ethanol (referred to as 'GEM').

[134] http://www.iea-amf.org/content/fuel_information/methanol, http://www.iags.org/Shanxi_trip_report.pdf

[135] https://www.ihs.com/products/methanol-chemical-economics-handbook.html

[136] DME is a gaseous fuel, whereas DMM/OME is a liquid drop-in fuel for diesel.

11.4 Status quo

According to the Methanol Institute there are over 90 methanol plants worldwide, with a combined production capacity of around 110 Mt (equivalent to around 138 billion litres)[137]. Global methanol demand reached 70 Mt (87 billion litres) in 2015. Capacity and demand is centred on China with an estimated 50% market share for both. European production capacity in 2012 stood at around 3% (2.9 Mt), mostly located in Germany and Norway, while consumption was around 7.5 Mt[138]. There is no methanol production in the UK currently.

Conventionally, methanol is commercially produced by natural gas reforming or gasification of coal. This involves the steam reforming of natural gas or partial oxidation of coal to produce syngas, a mixture of mainly H_2 and CO with smaller amounts of CO_2. The syngas is cleaned and then reacted under pressure in the presence of a metal catalyst[139] to synthesise methanol according to following two main equations:

CO (g) + $2H_2$ (g) → **CH_3OH** (l) (Methanol synthesis)
CO (g) + H_2O (g) → CO_2 (g) + H_2 (g) (Water-gas shift reaction)

The reaction is highly exothermic and a challenge is the removal of excess heat, in order to shift the equilibrium towards methanol production, and to avoid side reactions and catalyst sintering[140]. One application for the excess heat is on-site steam generation, reducing the overall natural gas consumption at the plant.

The primary feedstock for methanol production is natural gas, representing around 65% of global production, with 35% accounting for global production from coal (primarily in China)[141]. Alternatively, methanol can be produced from a variety of biogenic feedstocks (e.g. wood, paper pulp, black liquor, biogas), crude glycerine, biogas or municipal solid waste. The main conversion route is gasification and fuel synthesis. The crude syngas from biomass typically has a low hydrogen-to-carbon (H/C) ratio when compared with syngas from natural gas. To reach an optimal ratio of H_2 to CO molecules, syngas conditioning is performed after which it is converted to methanol in the presence of a metal catalyst[142]. This type of methanol is typically termed **biomethanol**. Companies developing biomethanol production facilities include Bio-MCN (Netherlands), Chemrec (Sweden) and Enerkem (Canada). Of these, Bio-MCN operate the world's largest biomethanol plant, a 440 kt/yr facility using biogas as the feedstock. It previously operated a 430 kt/yr plant, however this is currently mothballed.[143] The current deployment of biomethanol in the UK is around 30 million litres per year[144].

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[137] http://www.methanol.org/the-methanol-industry/
[138] http://www.sciencedirect.com/science/article/pii/S0306261915009071
[139] These potentially include: Copper oxide (CuO), Zinc oxide (ZnO) and Aluminium oxide (Al_2O_3).
[140] http://www.sciencedirect.com/science/article/pii/S0306261915009071
[141] IHS Chemical Bulletins – Insights, The changing face of the global methanol industry, available at: http://www.methanol.org/the-methanol-industry/
[142] These potentially include: Copper oxide (CuO), Zinc oxide (ZnO) and Chromium oxide (Cr_2O_3)..
[143] http://www.oci.nl/oci-fcg/our-facilities/biomcn/
[144] RTFO Biofuel Statistics, available at: https://www.gov.uk/government/collections/biofuels-statistics

According to the International Renewable Energy Association (IRENA)[145], the production cost of biomethanol in 2013 was estimated to be between 1.5-4 times higher than the cost of natural gas-based methanol[146]. Production based on CO_2 was estimated to be between €510-900/t. This is significantly higher than CRI's estimate that the cost of synthetic methanol is twice the cost of fossil methanol based on an electricity price of 30 €/MWh.

11.5 Current technology status

In our view the current TRL for this technology is **8**.

There are no commercial or pilot scale synthetic methanol production plants in the UK at this time. To date, two companies have developed synthetic methanol production plants: Icelandic company Carbon Recycling International (CRI) and Japanese company Mitsui Chemicals Inc. (MCI). Of these, CRI is the clear market leader, as detailed below.

Carbon Recycling International

CRI's George Olah Renewable Methanol Plant located in Svartsengi, Iceland began production in late 2011 and was completed in 2012. Prior to this CRI had operated a pilot plant at this site since 2007. All electricity used in the plant comes from the Icelandic grid, which is 100% renewable (generated from hydro and geothermal energy). CO_2 is captured from the flue gas released by a geothermal power plant located next to the CRI facility and would have otherwise been vented to the atmosphere by the geothermal plant during the generation of electricity. Future plants, in other countries, could instead be connected to other point sources, such as coal plants.

In 2015, CRI expanded capacity from 1.3 million litres per year to 5 million litres, equivalent to 4 kt/yr (utilising around 6 $ktCO_2$/yr). The company has overall ambitions to develop commercial scale plants of 63 million litres per year, or 50 kt/yr capacity (utilising around 72.5 $ktCO_2$/yr). The expected cost of a commercial scale plant is €50 million.

In addition, CRI has received two grants under Horizon 2020 to develop pilot scale projects. These projects are intended to demonstrate specific potential applications of the technology.

- **MefCO2 Project** (€11m awarded in 2015)[147,148]: The project aims to demonstrate the application of battery storage in power to fuels production and also the so called "load following concept" to demonstrate the utilisation of intermittent renewable energy sources. The availability of surplus renewable electricity (e.g. generated by wind or solar) determines the synthetic methanol production level. Production is "ramped up" when there is excess electricity and vice versa. The grant was awarded based on utilising CO_2 emissions from the Lünen coal power station in Germany, operated by STEAG GmbH. However, this power station is due to be decommissioned earlier than originally anticipated and so discussions are now underway for a new consortium partner to participate in the project.

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[145] https://www.irena.org/DocumentDownloads/Publications/IRENA-ETSAP%20Tech%20Brief%20I08%20Production_of_Bio-methanol.pdf

[146] The Methanex European Posted Contract for methanol price ranged from €320-340 in 2012, and €225-275 in 2016. See: https://www.methanex.com/sites/default/files/methanol-price/MxAvgPrice_Jan%2025%2C%202017.pdf

[147] http://www.mefco2.eu/

[148] http://www.steag-energyservices.com/es_presse_detail+M56afe7dd5a2.html; http://www.powerengineeringint.com/articles/2015/06/coal-plant-provides-co2-for-methanol-production.html

Other consortium partners include Mitsubishi Hitachi Power Systems Europe (system integrator), Hydrogenics (electrolysis unit) and several European universities and research institutes.

- **FReSMe Project** (€11m awarded in 2016)[149]: The project aims to demonstrate how residual blast furnace gases from steel manufacturing can be utilised in the production of synthetic methanol. A secondary aim is to demonstrate how H_2 streams can be switched between H_2 produced via electrolysis and by-product H_2 (the by-product H_2 providing base load production). The project will be located at the Swerea MEFOS steel manufacturing plant in Sweden. Consortium partners include SSAB and Stena over half a dozen industrial firms and research institutes, including Tata Steel (Netherlands), Kisuma Chemicals (Netherlands), Array Industries (Netherlands) and Dutch research institute ECN.

In 2013, Methanex (Canada), the world's largest methanol producer, announced a $5m investment in CRI, and more recently in 2015, the Chinese car manufacturer Geely Auto announced plans to invest $45.5m in CRI over a 3 year period. Geely and CRI intend to collaborate in the deployment of synthetic methanol fuel production technology in China and explore the development and deployment of 100% methanol-fuelled vehicles, with China and Iceland initial target countries.

In 2015, Perstorp (a major Scandinavian biodiesel producer) signed a long-term off-take agreement with CRI to use synthetic methanol produced for the production of biodiesel.

[See also Appendix 3 for a case study on CRI.]

Mitsui Chemicals Inc.
Early research into synthetic methanol synthesis from CO_2 and H_2 was undertaken by Mitsui Chemicals Inc. (MCI), who commissioned a 100 t/yr pilot plant in 2009 located inside its Osaka production complex (Japan)[150]. The plant utilises exhaust gas CO_2 from MCI's other plants, and surplus H_2 from other operational plants. MCI have been developing photo-catalyst material and solar cells for splitting water via electrolysis to provide renewable H_2, however, limited information is available on more recent developments, other than a brief summary that was included in the 2015 CSR report of Mitsui Chemicals Group. This stated that "*The current status is that we are continuing our investigations to improve commercialization accuracy, but the securing of hydrogen supplies is presenting a major hurdle. We are looking into biomass-derived hydrogen to overcome this problem*"[151].

Other initiatives
In 2011, Swiss company Silicon Fire AG had, together with the Technical University Munich announced plans to produce synthetic methanol[152], however no further publically available documents have been identified.

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[149] http://carbonrecycling.is/news/
[150] http://www.mitsuichem.com/release/2008/080825e.htm
[151] http://www.mitsuichem.com/csr/report/pdf/csr2015web_e.pdf (see page 89/207)
[152] http://www.silicon-fire.com/en/

11.6 Future growth potential to 2030

By 2030 the TRL is expected to reach **9**.

Summary

We see the **EU road transport fuel market** as the main potential deployment opportunity for synthetic methanol in the period to 2030. This is driven by the policy framework for renewable energy in transport that is currently in place and recently proposed for the period post-2020. CRI estimate that the maximum potential demand for methanol in the EU is around 10-15 Mt/yr. This is based on ethanol blending, synthetic methanol deployment and as methanol derivatives (including MTBE, DME, OME and MtG). Given the uncertainty regarding the deployment of high-blend methanol and methanol derivatives in the UK, and the barriers to deployment (see section 11.9), we propose to include a conservative estimate of **0-100 kt/yr** UK production in 2030. The associated CO_2 demand is **0-145 ktCO_2/yr**.

Demand for methanol has historically been very limited in the US. Outside of Europe and North America, there is in general a low demand for renewable fuels (including methanol). China stands out as a potential market for the future deployment of synthetic methanol.

We do not foresee significant demand for synthetic methanol in the marine sector to 2030. Furthermore, no deployment of methanol based fuels in aviation is estimated.

Our understanding is that the chemical sector is not prepared to pay a price premium for synthetic methanol in the period to 2030, given the highly competitive nature of the industry. In the long-term (post-2030) this dynamic may change, in particular if mandates for the use of green/low carbon chemicals are established.

Road transport sector

In the EU, the ILUC Directive (Directive (EU) 2015/1513) places a cap of 7% for the Member States on the contribution of crop-based biofuels in meeting the target of 10% renewable energy in transport by 2020. The directive also importantly introduces a new fuel classification of “renewable liquid and gaseous fuels of non-biological origin” – defined as a “*liquid or gaseous fuels other than biofuels whose energy content comes from renewable energy sources other than biomass, and which are used in transport*”. Synthetic methanol fits into this new classification. These fuels are “double counted” (energy basis) towards Member States 10% target. Member States have until September 2017 to transpose the ILUC Directive into national legislation, which will serve to stimulate the market for alternative renewable transport fuels, including synthetic methanol. The UK Department for Transport is currently consulting on the implementation of the ILUC Directive into the Renewable Transport Fuel Obligation (RTFO)[153].

On 30 November 2016, the Commission presented its draft proposal to review the Renewable Energy Directive for the post-2020 period as part of a Clean Energy Package. The EU executive proposes to reduce the contribution of conventional crop-based biofuels in transport from a maximum of 7% in 2021 to 3.8% in 2030. It also set an obligation to raise the share of other ‘low emissions fuels’ such as advanced biofuels, renewable fuels from non-biological origin and fossil waste-gas in transport to 6.8%.

[153] https://www.gov.uk/government/consultations/renewable-transport-fuel-obligation-proposed-changes-for-2017

The post 2020 policy proposal provides a strong signal to the market for alternative renewable transport fuels. However, there are several competing alternative transport fuels to synthetic methanol, which may make it challenging to create a significant demand (see Table 9).

Table 9. Overview of methanol fuel deployment options in road transport and their competing alternatives.

Vehicle type	Methanol fuel options	Competing fuel options
Heavy-goods vehicles	Methanol in dual-fuel operation with diesel, DME and DMM/OME	(Bio)diesel - including drop-in fuels like HVO and synthetic (Fischer-Tropsch) diesel[154], LPG, CNG, SNG and biomethane
Light duty vehicles	Methanol blending up to 100% (M100) - high blend levels require vehicle modification - and MTBE for gasoline and DME a replacement fuel for diesel	Biofuels, LPG, CNG, electric and hydrogen fuel cells

Deployment of alternative fuels are linked to a broader drive to reduce (diesel) engine emissions reductions in urban areas. However, at this time the potential environmental benefits of methanol as a fuel are not sufficiently well understood.

A major consideration is the extent to which methanol derivatives will compete against drop in fuels, like HVO. In this respect, it should be noted that the LowCVP Fuel Roadmap to 2030[155] does not specifically name methanol as a fuel option. In addition, methanol is currently not included in the EU Alternative Fuel Infrastructure Strategy (AFI) which Member States are required to implement between 2020-2030[156]. Based on this uncertainty, we propose to base the estimate of the deployment potential of synthetic methanol on the gasoline blending market.

Gasoline demand is currently around 12 Mt/yr in the UK[157]. No data is publically available on UK methanol blending rates, although CRI estimate that around 100 kt/yr of fossil methanol is blended (this is lower than a 3% blend rate which would be around 350 kt/yr) [158]. The recently proposed Clean Energy Package provides a major stimulus to the advanced fuel market with the inclusion of a 6.8% mandatory target for advanced biofuels and renewable fuels of non-biological origin (such as synthetic methanol). However, given the uncertainty regarding the deployment of high-blend methanol and methanol derivatives in the UK, we propose to include a conservative estimate of **0-100 kt/yr** synthetic methanol UK production in 2030 (equivalent to 2 x 50 kt/yr commercial scale plants). The associated CO_2 demand is **0-145 ktCO_2/yr**.

[154] Diesel produced via gasification of biomass and Fischer-Tropsch synthesis.

[155] http://www.element-energy.co.uk/wordpress/wp-content/uploads/2014/06/Element-Energy-_-Fuels-roadmap_29May2014.pdf

[156] https://ec.europa.eu/transport/themes/urban/cpt_en

[157] https://www.gov.uk/government/statistics/biofuel-statistics-year-8-2015-to-2016-report-6

[158] Personal communication with Benedikt Stefánsson (Dierctor of Business Development - CRI).

A potential interesting niche opportunity in the UK could be the deployment of high blend synthetic methanol in the iconic London Black Cab (the vehicle is manufactured by Geely who recently invested in CRI and already manufacture methanol vehicles[159]), although the fuel would need to be cost-competitive with alternatives for there to be sufficient take-up and meet air quality requirements in line with the Major's Air Quality Strategy[160]. Methanol could potentially be supplied via bunkered fuel depots located across the city. We do not, otherwise, foresee widespread adoption of high blend methanol in the UK.

As discussed above, in contrast to the EU, methanol (and MTBE) is not marketed in the US at the moment as a fuel. Producers could apply to do so, but the acceptance process for new fuel standards is understood to be very complicated and therefore acts as a barrier to its deployment. An alternative route is for producers to petition the Environmental Protection Agency to allow synthetic methanol to qualify for RINs under the Renewable Fuel Standard[161]. Oberon Fuels[162] are actively marketing DME as a fuel in the US. Should their market share grow, and assuming that there will be an extension to the RFS2 post-2022, then there will be increased demand for synthetic methanol.

Outside of Europe and North America there is, in general, a low demand for renewable fuels (including methanol), due to the lack of specific mandates for their deployment. China stands out as a potential key market for the future deployment of synthetic methanol, particularly given the recent tie-up between CRI and Geely and considering that methanol currently makes up around 8% of the gasoline fuel total. The methanol is primarily made from coal at present. Several Chinese provinces already have biofuel mandates in place.

Marine sector

The marine sector is a potential future growth area for renewable fuels, although it is not clear to what extent these are likely to be adopted at scale in the period to 2030. The main driver for their deployment is the restriction on sulphur oxide (SOx), nitrogen oxide (NOx) and particulate matter (PM) emissions from the use of marine fuels under the MARPOL Convention[163]. The current limit is 3.5% sulphur (mass basis), however this will be reduced to 0.5% from either 2020 or 2025 depending on the outcome of a review which will be completed in 2018. In addition, there are specific provisions – so called SOx Emission Control Areas (SECAs) - that apply to Europe (Baltic Sea, North Sea and English Channel) and waters within 200 nautical miles from the coast of North America.

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[159] http://carbonrecycling.is/news/2016/2/16/geely-group-invests-in-icelands-carbon-recycling-international-in-further-step-forward-for-new-energy-methanol-vehicle-efforts; http://carbonrecycling.is/news/2016/4/13/carbon-recycling-international-launches-fleet-test-of-geely-emgrand-7-methanol-powered-vehicles

[160] https://www.london.gov.uk/what-we-do/environment/pollution-and-air-quality/improving-air-quality

[161] The EPA recently ruled that the Joule process – ethanol production via solar and using bio-catalysis – was eligible to generate RINs.

[162] http://oberonfuels.com/

[163] Annex VI of the IMO Convention for the Prevention of Pollution form ships (MARPOL).

Low sulphur diesel regulations will require the sector to switch to cleaner alternatives than HFO (Heavy Fuel Oil), including LFO (Low Sulphur Fuel Oil) or otherwise to invest on-board sulphur abatement technology. Potential new fuels include LNG and methanol[164], which are both inherently low in sulphur. Each of these fuels have reported advantages and disadvantages. For example, methanol can be more easily retro-fitted as it is a liquid fuel, but would require a new fuelling infrastructure. A recent example of methanol deployment is the conversion of a Stena Germanica ferry in 2015 to run on methanol. Dual fuel technology is used, with methanol as the main fuel with the option to use Marine Gas Oil (MGO) as a back-up.

Initially, it is envisaged that (lower cost) fossil fuels will be deployed to meet these requirement. Deployment of renewable fuels may follow, although this is contingent on the maritime sector adopting decarbonisation targets. To this end, in October 2016, the International Maritime Organisation (IMO) laid out a strategy to address GHG emissions for ships greater than 5 kt (gross) from 2023[165]. This proposal may provide an opportunity for the deployment of alternative fuels, such as synthetic methanol. However, the potential will ultimately depend on the ambition level of the agreement, and the extent to which meaningful GHG reduction targets are set in the period to 2030 (and furthermore whether compliance can be met through the purchase of carbon offsets as is the case with aviation).

The global demand for marine fuels is estimated to be between 300-400 Mt/yr (JRC, 2016). Of this, CRI estimate that the total demand in the Baltic and North Seas is 30-40 Mt/yr methanol equivalent[166]. Without further details on the ambition level of the IMO proposal it is not feasible at this time to provide a robust estimate of the deployment potential of synthetic methanol deployment in the maritime sector to 2030.

Aviation sector

The deployment of sustainable alternative aviation fuels received a boost with the recent agreement by ICAO to introduce a Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA)[167]. CORSIA will begin with a pilot phase from 2021 through 2023, followed by a first phase, from 2024 through 2026. To date, so-called HEFA fuels (produced through the hydrogenation of vegetable oils and fats) have received most interest, and are likely to be deployed initially. Methanol cannot be used directly as an aviation fuel due to its low energy density, without further synthesis.

11.7 Locations for deployment

There are no existing facilities in the UK producing synthetic methanol. To identify potential future locations some key aspects should be considered:

- The availability of CO_2 sources with a quality range compatible for synthetic methanol production process. After carbon capture the minimum quality needs to be 99% purity at the inlet to the reactor.

[164] Both fuels are explicitly mentioned by the IMO, see: http://www.imo.org/en/MediaCentre/HotTopics/GHG/Documents/sulphur%20limits%20FAQ_20-09-2016.pdf

[165] http://www.imo.org/en/MediaCentre/PressBriefings/Pages/28-MEPC-data-collection--.aspx

[166] Personal communication with Benedikt Stefánsson (Director of Business Development - CRI).

[167] http://www.icao.int/Newsroom/Pages/Historic-agreement-reached-to-mitigate-international-aviation-emissions.aspx

- Areas with a high deployment of (renewable) electricity to utilise surplus electricity that would otherwise need to be curtailed. This could, for example, include a direct connection to a wind or solar farm, or a grid connection in an area with a high density of renewable energy. Alternatively, if synthetic methanol plants are deployed to provide grid ancillary services (such as Demand Turn Up), then there is no specific constraint on location other than access to the electricity grid. (Ultimately access to low cost electricity is fundamental to the business case for this technology.)
- Proximity to a source of by-product H_2. Potential sources of H_2 include chlor-alkali production facilities or coking gas from steel manufacturing. If the proposed Leeds H21 hydrogen project were to go ahead, this would be an ideal opportunity for synergistic colocation. In these cases H_2 production via electrolysis is substituted with H_2 capture and purification. However, due to the high cost of transporting H_2, it either should be produced on site or close to methanol production facility.
- Preferably a site near/in an industrial location with availability of land and proximity to a CO_2 source. It does not exclude the possibility of a standalone site as long as the CO_2 supply is sufficient.

Example locations/areas fulfilling these location criteria are:

- Runcorn (INOVYN – joint venture between INEOS ChlorVinyls and Solvay) utilising H_2 from chlor-alkali production.
- Port Talbot (Tata Steel) and Rotherham (British Steel) utilising H_2 extracted from coking gas from steel manufacturing blast furnaces.
- If the proposed Leeds H21 hydrogen project were to go ahead, this could provide an ideal opportunity for synergistic colocation.

11.8 Benefits and opportunities

The problem of poor air quality in urban areas caused, in particular, by road vehicles running on diesel is fast rising up the agenda in the UK. Switching to synthetic methanol (or its derivatives) could potentially help companies meet more stringent (non-CO_2) emission targets for vehicles, subject to verification of engine performance.

As discussed in section 11.6, the deployment of synthetic methanol counts towards UK and EU Member State renewable transport targets. Furthermore, the announcement by the IMO to address GHG emissions in shipping may provide an opportunity for synthetic methanol deployment beyond 2023.

Finally, in April 2015, the UK government introduced a reduced duty level for aqua methanol (95% methanol /5% water) used as a fuel, set at 7.9p/l[168].

[168] https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/385194/TIIN_8093.pdf

11.9 Barriers and required support

Synthetic methanol faces a number of barriers to deployment. These include:

- **Cost:** Synthetic methanol is estimated to be at least twice the cost of conventional methanol. This will serve as a key barrier to its deployment in the chemical sector, which is not expected to mandate the use of green/low carbon chemicals in the period to 2030. Synthetic methanol (and its derivatives) will need to compete on cost with other low carbon fuel alternatives that can be deployed in the road transport sector. A detailed analysis was not within the scope of this study.
- **Lack of "surplus" renewable electricity:** The UK's electricity system is not currently characterised by significant quantities of surplus electricity.
- **Restriction of methanol blending:** Current demand for methanol in the EU automotive sector is mainly limited to ethanol blending. The Fuel Quality Directive and the EN 228 standard effectively restricts the methanol blend to 3% by volume. The UK Petroleum Industry Association (UK PIA) is not aware of any discussions to increase the blend limit, and consider it unlikely that the automotive industry would support any increase to the methanol content of petrol. The European Automobile Manufacturers Association published a position paper in 2015, that concluded that, "*Due to the above mentioned drawbacks for direct blending of methanol in gasoline, the existing ban of methanol, respectively low usage (less than 3 vol %) in most of the existing fuel standards worldwide, is strongly confirmed and highly recommended*"[169].
- **No restriction on fossil methanol in EU biodiesel:** Methanol is used as a reagent in the production of biodiesel (FAME), although there is no requirement to use synthetic methanol.
- **Competing fuel options:** There are a number of competing fuel options for methanol, both with conventional fuels and alternative low-carbon/renewable fuels. However, the LowCVP Fuel Roadmap to 2030 does not specifically name methanol (or its derivatives) as a fuel option.
- **Policy environment outside Europe:** Outside of Europe and North America, there is in general a low demand for renewable fuels (including methanol), due to the lack of specific mandates for their deployment.
- **Vapour pressure of methanol:** Methanol blending in gasoline changes the vapour pressure of gasoline. This requires refiners to make adjustments to their existing processes which results in additional cost. Removing volatile components from gasoline increases the cost of production, as the volatile components cost less than stable components. Changing the blendstock properties to enable further blending with methanol, or other oxygenates such as ethanol, is therefore not particularly attractive for fuel suppliers.
- **Lack of existing methanol fuelling infrastructure:** Methanol is soluble in water and as is the case with ethanol blending, requires 'dry' infrastructure. Although additional blending of methanol as a component in gasoline does not require separate fuel pumps or underground tanks, if pure methanol or higher methanol blends were to be distributed, existing UK distribution and storage infrastructure would need to adapted. High blend methanol will also need to be bunkered separately, and not all forecourts could accommodate new retail pumps or storage.
- **Toxicity:** Methanol is neurotoxic. The UK would need to establish an HSE code of practice for the storage, handling and transport of methanol (although international codes developed by the Methanol Institute already exist[170]).

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[169] ACEA Position Paper on Methanol as a Gasoline Blending Component, available at: https://www.acea.be/uploads/publications/021015_ACEA_position_paper_on_methanol_as_a_gasoline_component.pdf

[170] http://www.methanol.org/wp-content/uploads/2016/06/Methanol-Safe-Handling-Manual-Final-English.pdf and http://www.methanol.org/safe-handling/

- **Air quality:** The benefits of using synthetic methanol from an air quality perspective are not clearly understood in the UK. The LowCVP is not aware of any emission performance testing on methanol as a fuel for the most recent versions of engines. This would need to be provided by the automotive industry. This information is particularly relevant to the heavy goods market and would need to be better understood if methanol (or its derivatives) are adopted.
- **LCA methodology in EU:** The proposed LCA methodology developed for synthetic methanol and other RFNBOs was outlined in the Commission's Clean Energy Package, but not yet formally agreed. Default values are not yet available[171]. Stakeholders had until March 2017 to submit data to the Commission for consideration in the calculation of default values; thereafter the JRC will calculate the default values on behalf of the Commission. Until this time there is uncertainty in the GHG emission performance of the fuel, which is seen as a barrier to investment by some industry stakeholders.
- **Vehicle warranty:** Our understanding is that engine manufacturers do not currently provide warranty at high methanol blends. Similarly, we are not aware of companies retro-fitting diesel engines to run on methanol for the same reason. If incentives for engine retrofits are available then a wholesale transition of market to high methanol blends can take place.
- **Energy density:** The energy density of methanol is less than other liquid fuels (e.g. 20 MJ/kg compared to 43 MJ/kg for gasoline).
- **Low investor confidence surrounding renewable transport fuels in the UK/EU:** There has been significant EU policy uncertainty regarding biofuels in recent years, in particular resulting from the protracted discussions surrounding the publication of the ILUC Directive. The knock-on impact of this in the UK was that the fuel supplier obligations in the RTFO were not increased for several years. This has led to a deterioration in the investment case in the UK and the EU. Although, the status of synthetic methanol was also until recently uncertain, this has been resolved following the publication of the ILUC Directive and proposal to amend the RED.
- **No requirement to use renewable fuels in the marine sector:** Low sulphur diesel regulations will require the sector to switch to cleaner alternatives than the incumbent fuel, HFO in Europe and North America or otherwise require an investment in an on-board scrubber. Cleaner alternatives include LFO and potential new fuels such as LNG and methanol. However, in the absence of a mandate it is expected that (lower cost) fossil fuels will be deployed. The recently announced IMO strategy to address GHG emissions in shipping may provide an opportunity for the deployment of alternative fuels, such as synthetic methanol, post-2023. However, the deployment potential will ultimately depend on the ambition level of the agreement, which is unclear at this time.

Support to address these barriers, could consist of:

- Funding on vehicle compatibility and engine testing could help to remove some of the barriers identified above.
- Continuation of the low duty rate for aqua methanol to promote uptake.

[171] https://ec.europa.eu/clima/sites/clima/files/transport/fuel/docs/novel_transport_fuels_default_values_en.pdf; http://ec.europa.eu/energy/sites/ener/files/documents/1_en_act_part1_v7_1.pdf

12 Conclusions

Each CCU technology is at a different stage of development and faces different barriers to reach full commercialisation. However, some of the selected technologies share common characteristics and face similar challenges. Below we have summarised the identified **cross-cutting opportunities and barriers across the selected technologies**. These form the basis for identifying the types of support which could advance the development of these CCU technologies and CCUS technology in general, if the support was deemed to be warranted in light of potential contribution to a) the UK's economy and b) climate change mitigation.

1. **Goods produced from CCU technologies can serve as low-carbon alternatives to existing products.** By using CO_2 as an input material instead of fossil fuel-based feedstock and/or energy, the CO_2 footprint of the CCU products could be significantly lower provided the process is efficient in its use of other materials and energy, and the other inputs do not place undue carbon burdens on the process. Synthetic methanol is chemically the same as fossil fuel-based methanol, which is used for fuel blending in the UK, or as a feedstock in the chemical sector. Synthetic methane can replace natural gas and be fed into the existing gas grid or used as a low carbon transport fuel. In horticulture, by using industrial CO_2 glasshouses do not have to utilise on-site CHP installations that generally run on natural gas (provided that a waste heat source is also available). Concrete curing and novel cements reportedly can reduce the traditional cement demand significantly in the production of concrete products. Carbonation products can replace energy-intensive products used in the construction and chemical sectors. This replacement effect is also the primary driver of the CO_2 abatement impact of CCU technologies. While the CO_2 stored in horticulture, synthetic methane, synthetic methanol is short-lived, the CO_2 stored in mineralisation CCU products is permanent. CO_2-based polymer processing can potentially store the CO_2 for decades, but not permanently.

2. **Cost acts as a barrier to the uptake of some of the selected CCU technologies.** The development of synthetic methanol and methane is advancing with several pilot plants around the world. Although the products produced from these technologies and their fossil fuel-based alternatives are fungible, the CCU products are currently much more expensive. Synthetic methanol is estimated to be at least twice the market price of conventional methanol and synthetic methane may be up to five times more expensive than natural gas. The availability of low cost industrial CO_2 is a key limiting factor for its use in horticulture and emitters have little incentive to capture, condition and transport CO_2 to glasshouses as it is not their core business. Businesses that do currently capture and sell CO_2 to the horticulture sector at a CO_2 price that is typically only marginally cheaper than the CHP alternative. The UK horticulture sector therefore has very limited industrial CO_2 demand. Another barrier is that the application of CCU technology would require significant new investments into CO_2 capture and transport infrastructure. Furthermore, most CCU technologies are still at the pilot scale and hence scale up is required to reduce costs.

3. **Some CCU products are reportedly cheaper to produce than their conventional counterpart, but the market is hesitant to widely adopt the products.** CO_2-based polymers are in some cases reportedly cheaper to produce than their petroleum-based equivalents, e.g. in the case of polyether polyol they may be 15-30% cheaper. A key risk is the acceptance of CO_2-based polymers by downstream companies that are purchasing the polymers to use in end-use applications. The acceptability is likely to vary between applications, and this will determine how quickly CCU polymers can be deployed in the market.

This is also the case for the mineralisation CCU technologies, whose primary customer segment is the construction sector. Concrete curing and novel cements have been claimed by the technology providers to lower costs substantially as they could provide stronger concrete, while lowering the time of the curing/weathering process and reducing the overall demand for cement. Carbonated materials can be produced more cheaply compared to traditional building materials; e.g. the cost of Carbon8 aggregate is reportedly up to three times lower than conventional secondary aggregate. However, the construction sector is generally conservative in nature and reluctant towards using new building materials that have not been proven for a long period in-situ (15-20 years).

4. **The hesitation in the market to use some CCU products is that they *may* have certain perceived disadvantages compared to conventional products or their substitutes.**
Recycling of polymers almost certainly makes more sense environmentally and economically than producing new CO_2-based polymers. The construction industry is unlikely to widely adopt concrete curing and novel cements without independent testing of their reliability, particularly in reinforced concrete applications. Observers have suggested that heavy metals within carbonated block materials could potentially leech. Fear of such leaching might lead to public resistance and slow their uptake. The development for carbonation is further limited by the availability of waste streams due to companies already having long-term contracts with existing waste companies. There is a limited interest from industrial plants to capture and transport CO_2 to CCU facilities as it is not their core business. For example, investing in CO_2 capture, cleaning and transport infrastructure specifically for use in horticulture would bring additional risks to the company. For the horticultural sector this also brings additional risks, as they are not in control of their CO_2 and heat supply. An industrial plant outage would set-back production and necessitate the purchase of more expensive CO_2 from the bulk market.

5. **Uncertainty in the way to account for and value the CO_2 emission reductions (and potentially the extent of such reductions) from CCU products is limiting the uptake of the technology as an abatement measure.**
There is currently limited information on the carbon abatement potential for candidate CCU technologies. In addition, there is no formally agreed LCA methodology with which calculations should be performed. Addressing these aspects is critical if CCU technologies are to be promoted as a carbon mitigation option. Furthermore, the CO_2 emission reductions achieved by utilising and storing the CO_2 in the products are not often not accounted for in many emission reduction policies such as the EU ETS. While this can be justified for CO_2 emissions where storage is only short-lived, with the mineralisation CCU technologies the CO_2 is sequestrated permanently. CO_2 stored in CO_2-based polymers is relatively long-lived, but such polymers will decompose after 50 or so years and so do not offer long-term mitigation potential. If these CO_2 benefits could be accurately valued, this would improve the ability to construct a business case for these technologies. In addition, this would help to drive investment in those technologies that offer the greatest carbon abatement potential.

6. **The future estimated CO_2 demand from the application of the selected CCU technologies is modest and limited to around 113-624 ktCO_2/yr by 2030, less than 1% of the current CO_2 emissions in the UK:**
   - Industrial CO_2 use in horticulture is expected to account for around a third of the total future maximum CO_2 demand from the selected CCU technologies. A range of 108-218 ktCO_2/yr is estimated. The range is related to the expected planted areas in greenhouses and a CO_2 utilisation rate of 5-10% across the industry. (Note, however, that around 80% of the CO_2 used is vented without uptake in the crop.)
   - Synthetic methanol could potentially provide a CO_2 demand in the range of 0-145 ktCO_2/yr, based on the deployment of up to two commercial scale plants with a capacity of 50 kt/yr synthetic methanol each.

- Concrete curing could have a maximum CO_2 demand of around 100 ktCO_2/yr, assuming full optimisation of the technology in the UK.
- CO_2-based polymer processing is expected to have a maximum CO_2 demand in the range of 0-100 ktCO_2/yr based on the deployment of up to two 100 kt/yr commercial scale CO_2-based polymer plants, and assuming a 50% CO_2 uptake. (The CO_2 uptake could feasibly range from 15-50%, therefore this estimate represents a maximum.)
- Carbonation is estimated to have a CO_2 demand of 5-43 ktCO_2/yr. This assumes that 240 kt/yr of APCr and 120 kt/yr of steel slag or cement waste is treated through Carbon8's ACT process. Additional potential could arise from one-off soil remediation projects. The long-term potential is limited as waste streams are expected to decrease with the decline in steel production and closure of unabated coal-fired power plants.
- Synthetic methane is estimated to have a potential CO_2 demand of 0-18 ktCO_2/yr, assuming a total production capacity of around 10 Mm^3.
- No projections for the CO_2 demand for novel cements were made in this study, as their deployment will require long-term trials and tests which, given the early stage of development of this technology, is not expected to be feasible by 2030.

The growth in demand for CO_2 is primarily restricted by the anticipated market demand for CCU products, suitable locations with sufficient CO_2 at the right quality and access to other raw materials.

7. **Despite some potential for CO_2 demand for CCU outside the UK, the market for CO_2 export is very limited.**
The expected CO_2 demand across Europe by 2030 is in the order of 10 times larger than in the UK. Globally, this potential CO_2 demand is about a factor 1,000 lower than the CO_2 produced. It is very difficult to access these markets as a key factor to make the business case for CCU technologies is that the facility is relatively close to a suitable CO_2 source. The only CO_2 market that the UK might be able to target is the European beverage/food-grade CO_2 market (e.g. export of CO_2 to serve the Netherlands for use in greenhouses). This will depend on the development of carbon capture and purification technology in the UK and the market price for the CO_2.

8. **Other countries are leading the research and development of many CCU technologies. The UK therefore needs to act quickly if it is believed that there will be a significant future market for CCU technology and benefits to the UK.**
Many CCU technologies are already being developed outside of the UK and the market for many products made from CCU technologies in the UK is currently non-existent. The market leader for synthetic methanol production is an Icelandic company, which has a pilot plant in Iceland and two planned demonstration projects in Europe. Germany is the market leader for synthetic methane, with 2 operational Power-to-Gas plants feeding synthetic methane into the gas grid (and over 20 plants Power-to-Gas plants producing H_2). UK company, ITM Power, is active in supplying rapid response electrolysers for these projects though. Concrete curing and novel cement technologies are being developed by 20-30 companies, universities and research institutes around the world, with leading companies situated in North America. The UK has a few projects on industrial CO_2 use in horticulture, whereas the Netherlands is the clear market leader. There are several tens of companies and research institutes around the world working on carbonation technology with several pilot plants in the United States as well.

One specific carbonation technology that the UK is a market leader is accelerated carbonation technology (ACT), Project developer Carbon8 have commissioned two UK plants to date and aim to have 5-6 plants in operation by 2021. Finally, there is one company in the UK (Econic Technologies) working on catalyst development for CO_2-based polymer technologies, but it faces significant competition from several large chemical companies around the world, including Saudi Aramco, who already have pilot plants in operation. UK polyol production, which uses the products from CO_2-based polymer processing, is currently non-existent, so there are no opportunities for retrofitting plants. However, there is a business case that can be made to invest in new capacity.

9. **The CCU technologies can be applied either to industrial clusters or standalone facilities, this is not a key criterion as long as the location criteria are met.**
The availability of suitable CO_2 sources is a key factor for all CCU technologies, although other factors apply. The purity of CO_2 and the acceptable distances from CO_2 sources differs per technology.

For example, **synthetic methanol** requires a purity of 99% CO_2 at the inlet to the reactor, whereas for **synthetic methane** the CO_2 quality can vary depending on the methanation process used. Important for synthetic methanol, and synthetic methane is the access to low cost renewable electricity for the electrolyser or proximity to a renewable or by-product H_2 source (purposely produced H_2 from fossil fuels is not considered low carbon synthetic methanol or synthetic methane in this study). For synthetic methane, proximity to a gas distribution network and gas grid connection is necessary. Possible synergies exist for co-locating a synthetic methane plant with a fermentation process, biomethane injection plant, water treatment plant or bio-SNG plant (as these may provide a CO_2 source and allow gas grid connection costs to be shared). Access to potable water is required for both these technologies for the electrolysis step.

For **horticulture**, the purity of the CO_2 and transportation distance of CO_2 are limiting factors. Typical distances in the Netherlands are 10 km for CO_2 and 5 km for heat, which are likely to serve as a reasonable proxy for the UK. The CO_2 produced needs to be in almost pure form (food grade) and continuous, and there should also be a continuous heat source present. Waste-to-energy or biomethane plants are seen as providing a good fit. The land close to industrial installations might be more expensive as these locations are likely to be zoned as industrial land and therefore command substantially higher land prices than agricultural land. Finally, good infrastructure connections to enable produce to be distributed to market are needed. The location of future CCU projects could target existing growers which are predominantly clustered in East Yorkshire/Hull area, Lea Valley and Thanet regions.

Carbonation is also restricted by the infrastructure present. Ideally, carbonation plants are located close to suitable waste streams (i.e. near steel, cement or waste-to-energy plants), CO_2 sources and the point of sales (co-located with existing concrete block manufacturing). An advantage of carbonation plants is that they do not need a high purity CO_2 source. Close to the point of sales might therefore be more important for the business case than proximity to CO_2 sources, also because the cost of transporting the carbonation products may be higher than the cost of transporting the waste (particularly in the case of combustion ashes). For steel and cement plants, or historical waste deposits, plants are likely to be located at, near to, the site where the waste is located. In the UK, the Teesside Collective see very good opportunities for carbonation in their region. Teesside has availability of sufficient CO_2 at different purity levels and also significant availability of waste materials, including historical steel slag deposits. Other (former) industrial regions with access to waste streams would also be well suited for the technology.

Concrete curing and novel cements can make use of existing pre-cast concrete plant production facilities, which will be the main factor determining the location. Some plants are reasonably near to industry clusters with potential availability of infrastructure for transporting the CO_2. Otherwise, the CO_2 would need to be trucked in. The technology can also be applied during the solidification process of ready-mix concrete at/near to the site where the concrete is being used (up to a maximum distance of 8 km from the site). In this case it is likely that the CO_2 will be transported by truck to the site. For novel cements, it is likely that plants would be located near to a port since we are unaware of any significant magnesite deposits in the UK.

For CO_2-based polymer processing, the important considerations are to identify existing production streams and assets with synergies to the production processes of CO_2-based polyols and the availability of CO_2 source with a quality range compatible for use in polyol production. The possibility of converting existing redundant facilities to production units for CO_2-based polymers can be explored, or if not available, cheap land availability for new facilities is key. Three example locations in the UK meeting these criteria include, the Tees Valley Process Industry Cluster, Grangemouth and Fawley and Hythe.

10. **Other benefits may be more important than the CO_2 benefits and can make the business case for the CCU technology.**

Benefits of the CCU technologies range from purported improved product attributes and enhancing the energy security of the UK to supporting the development of CCUS infrastructure and industrial clustering. If the monetary value of these benefits could be quantified and realised, this would improve the business case for CCU technologies:

- **Synthetic methanol and synthetic methane** can be used to provide grid ancillary services by turning excess electricity, which would otherwise be curtailed, into H_2. This is likely to become more relevant in the period to 2030, if increased (solar and wind) renewable electricity continues to be deployed. However, it is necessary to consider the overall system cost imposed by increased quantities of intermittent renewables onto the grid, together with the capital cost of electrolysers.
- **Synthetic methane** enables the existing gas grid infrastructure and consumer appliances to be used without modification (unlike H_2).
- **CO_2-based polymers** replace environmentally polluting feedstocks. Not only is the CO_2 footprint of polymers is reduced, but also the natural resources used associated with extraction of petroleum and air pollution from processing the feedstocks into raw material for polymers as well. CO_2-based polymers also enhances cluster development and industrial symbiosis, making use of the existing infrastructure for producing polymers.
- **Horticulture** can potentially utilise industrial CO_2 and heat at more stable competitive prices compared to natural gas and provide a new revenue stream for emitters. Horticulture can also share the CO_2 capture and transport infrastructure for other facilities. Due to the high CO_2 purity needed in horticulture, scaling up industrial CO_2 use in horticulture could further aid in the development of purification systems to clean CO_2 from coal, oil or biomass combustion where there are limited options available in the market. An opportunity is to make use of food-grade CO_2 from biogas upgrade that is currently not being used in the beverage industry when the biogas originates from waste. Finally, supermarkets can use industrial CO_2 use in horticulture to boost their “green” credentials compared to conventional glasshouse practices that generate additional CO_2.
- **Concrete curing** can also reportedly take place in less time, saving costs. **Concrete curing and novel cements** can further support clustering development as it can be applied to existing concrete plants and CO_2 capture and CO_2 utilisation technology development through application in facilities.

- **Carbonation** can treat (hazardous) waste streams and turn waste into useful products such as building materials and aggregates instead of the treated waste ending up being landfilled. It also makes use of local UK resources, whereas for products made through conventional production processes material may need to be imported. The technology is particularly suitable for development in industrial clusters, providing an alternative way for waste treatment in steel, cement and waste-to-energy plants and helping the development of both carbon capture technologies as well as the associated CO_2 infrastructure.

13 Recommendations

In this chapter, we provide recommendations on innovation support that can serve to advance CCU technologies and identify next steps, building on the analysis on barriers facing the CCU technologies (see chapters 5-11) and conclusions drawn in chapter 12.

13.1 Advice on innovation support

Potential support measures which would facilitate commercial development of CO_2 utilisation in the UK are detailed below, should it be desired to do so. Government and other stakeholders, including the private sector, could provide such support, with the most urgent need being to fully assess the life cycle emissions of any CCU technologies which are proposed for support.

1. **Raise awareness in CCU products both among private sector parties and the wider public, for example,** for example through:

    - **Detailed LCA for selected CCU processes:** One key finding is that evidence is lacking in a number of areas regarding the lifecycle emissions from CCU processes; it is particularly important to conduct consequential LCA based on recognised standards in areas such as accelerated carbonation and novel cements where natural carbonation occurs.
    - **CCU material testing:** Providing support for trials that aim to demonstrate the long-term durability of products used in the construction sector.
    - **Industry/Public awareness:** Further promoting the benefits and business opportunities of CCU in the UK – including to companies, local government and regional/sector organisations. Dissemination of international best practice and case studies, in particular those in the UK.
    - **Product standards and labelling:** The development of product standards and labelling schemes for CCU products would provide confidence to the market and help to stimulate their uptake by the end-consumers.

2. **Providing a financial incentive aimed at accelerating investment in CCU technology development**, for example through:

    - **Demonstration competition:** Government could provide funding for a CCU demonstration competition to help companies bring technologies to market, though any such funding must include a requirement for an independently audited LCA and techno-economic analysis demonstrating scalability of the process prior to large-scale funding (this could sensibly be a stage-gate in the work). Industrial co-funding of a significant share of the cost would demonstrate that companies consider these technologies to be potentially profitable with their internally projected CO_2 price.
    - **Supporting R&D:** Providing (financial and technical) support to UK R&D in CCU technologies, particularly with a view to de-risking and scaling up promising existing innovations rather than promoting new innovations; the latter is covered well by the investments in fundamental R&D. Innovate UK would be well placed to co-ordinate this. Promising innovations are those that meet three key criteria: 1. a good overall (net negative) carbon balance; 2. are of a material scale; 3. products that have the potential to be (broadly) economically competitive.
    - **Finance:** Work to help de-risk (first-of-a-kind) CCU projects. For example, through providing government guarantees, or providing access to low cost finance.

3. **Strengthening knowledge transfer involving key stakeholders including CO_2 emitters and potential users of CCU products**, for example through:
    - **CCU knowledge transfer network in existing networks**: Stimulating multi-stakeholder discussion of CCU with the aim of accelerating its uptake in the UK and identifying quick wins that can be realised. Relevant stakeholders are the scientific community, industry (including cluster and sector associations), investors, Local Enterprise Partnerships (LEPs) and national government. LEPs and industry cluster associations are seen as key stakeholders in this process as they are best placed to identify opportunities for industrial symbiosis.
    - **International:** The UK could play an active role internationally in the field of CCU. This would provide opportunities for international exchange of lessons learned or cooperation. Such a collaboration would also help to showcase UK companies active in CCU. (The Department of International Trade could also facilitate in this respect.)

Any actions taken should align with the aims of the recently published government Green Paper, “Building our Industrial Strategy”[172].

13.2 Next steps

This study has helped to further the understanding of the potential opportunities for CCU in the UK and increased awareness of CCU technologies and their benefits. We nonetheless, see a need for further research in this area to build on the findings in this study, in particular in the following areas:

- **LCA:** As identified in chapter 4 there is a lack of publically available LCA studies on CCU in general, and in particular for some technologies. Furthermore, there is no commonly applied LCA calculation methodology for CCU. The UK could take the lead in this area given its expertise in LCA and in setting internationally recognised carbon accounting standards (e.g. PAS 2050[173]).
- **Techno-economic assessment:** A detailed techno-economic evaluation of technologies would help BEIS to better understand which (type of) CCU technologies offer the best potential and over what timeframe, and to validate claims on technology performance that some technology developers have made, particularly considering the materiality and economic criteria which complement the LCA.
- **CO_2 mapping:** Detailed mapping of CO_2 sources and corresponding quality or purity with potential demand to identify ‘concrete’ CCU opportunities in terms of nature of process, location and scale.
- **Waste mapping:** A detailed audit of the alkaline waste streams available in the UK (historical, current and projected) will facilitate understanding of the potential CO_2 abatement opportunities using carbonation CCU technologies.

Finally, there is a need to understand better the CCU opportunities for other technologies that were not the main focus of this study to avoid having implicitly picked “winners”. This will also importantly help to build up a more representative picture of the total potential for CCU in the UK. Consideration of the potential beyond 2030 should also be explored given that some technologies are at an earlier stage of their technical development.

[172] https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/586626/building-our-industrial-strategy-green-paper.pdf

[173] http://shop.bsigroup.com/en/Browse-By-Subject/Environmental-Management-and-Sustainability/PAS-2050/

Appendix 1: Long list of CCU technologies

Table 10. Overview of initial long list of CCU technologies.

CCU category	CCU technology	Description	UK demand 2016	UK demand 2030	Global demand 2016	Global demand 2030	Current TRL	Timeframe to reach TRL 9
Chemicals production	Formic acid	Electrochemical reduction of CO_2 (ERC) combines captured CO_2 and water to produce formic acid (HCOOH) and O_2. The formic acid can be used in conventional applications (e.g. food preservative or antibacertial agent) or as a H_2 carrier in fuel cells (for use in transportation; CHP units etc); H_2 is released from the liquid formic acid as required when an aqueous solution of formic acid is exposed to an appropriate catalyst).	None	Very low	Very low	Very low	6-7	2026-2030
	Other (non-fuel) chemical synthesis	A wide array of other potential applications for CO_2 in the manufacture of bulk chemicals exists. Many of these developments are at the theoretical level, whilst others are at the laboratory stage of R&D. Potential applications include: acrylic acid from ethylene and acetone fermentation; aliphatic aldehydes from alkanes. Research into innovative chemical conversion processes, in particular the mimicking of natural photosynthesis, which involves conversion of CO_2 through photo-chemical, electrochemical and biochemical reactions to produce high energy carbohydrates (as in plants) is also underway. Photo-catalysis is also considered promising as a means to extend artificial photosynthesis beyond carbohydrate production into other chemicals. Electrochemical reduction of CO_2 using renewable energy could also provide new pathways for production of methane, methanol and formic acid (see 'CO_2 to fuels').	None	None	None	Very low	3	>2030
	Polymer processing	Polymers are large molecules composed of repeating structural units. Although polymers are often referred to as plastics, they actually consist of both natural and synthetic materials with a wide variety of properties. A new approach to polymer processing is to use CO_2 in combination with traditional feedstocks to synthesise polymers. This technology allows the use of waste CO_2 and transforms it into polycarbonates. The polymers that can be created with this technology are polypropylene carbonate (PPC) and polyethylene carbonate (PEC).	None	Low-Medium	Very low	Medium	8	2020-2025

CCU category	CCU technology	Description	UK demand		Global demand		Current TRL	Timeframe to reach TRL 9
			2016	2030	2016	2030		
	Sodium bicarbonate	Soda ash is a chemical used in a wide range of production applications, principally glass making, as well as domestic cleaners. It is manufactured through two methods: (1.) natural (from trona) or (2.) synthetic (using brine – the Solvay Process). The Solvay Process involves the addition of CO_2 to ammoniated brine which leads to the precipitation of sodium bicarbonate, which is processed to form soda ash. CO_2 is also required in other parts of the process.	Low	Low	Low	Low	9	<2016
CO_2 mineralisation	Bauxite residue carbonation	The extraction of alumina from bauxite ore results in a highly alkaline residue slurry (known as 'red mud'). A technology has been developed by Alcoa whereby concentrated CO_2 is used as a means of treating the highly alkaline by-product (pH=13). The process provides direct carbonation of the bauxite residue, locking up CO_2 and reducing the pH of the slurry to a less hazardous level.	None	None	Very low	High	9	<2016
	Carbonate mineralisation (Carbonation)	Carbon mineralisation is the conversion of CO_2 to solid inorganic carbonates using chemical reactions. Mineral carbonation occurs naturally and is a very slow process. In order for carbonate mineralisation to be a viable method to capture and reuse CO_2 from anthropogenic sources such as coal-fired power plants, this process must be accelerated considerably. The carbonates that are produced are stable over long time scales and therefore can be used for construction, mine reclamation or disposed of without the need for monitoring or the concern of potential CO_2 leaks that could pose safety or environmental risks.	Very low	Medium-High	Very low	High	4-8	2016-2019 (Accelerated Carbonation Technology) to >2030
	Concrete curing	Concrete curing is an important application, to achieve best strength and hardness. This happens after the concrete has been placed. Cement requires a moist, controlled environment to gain strength and harden fully. The cement paste hardens over time, initially setting and becoming rigid, gaining in strength in the weeks following, as a series of hydration reactions occurs. Instead of using traditional energy intensive steam curing methods an alternative method reusing CO_2 can be used. Adding CO_2 during this process changes some of the reactions occurring. This method, developed by Carbon Cure, makes use of CO_2 to enhance the cure of precast concrete products. It is purported to enhance the concrete strength.	None	High	Very low	High	Concrete curing: 7-8 Novel cements: 3-6	2026–2030 and >2030

CCU category	CCU technology	Description	UK demand 2016	UK demand 2030	Global demand 2016	Global demand 2030	Current TRL	Timeframe to reach TRL 9
CO_2 to fuels carrier	Algae cultivation	Algae cultivation using nutrient-rich, typically saline or brackish water in open ponds or closed bioreactors, where CO_2 is bubbled through to accelerate biomass production rates/yield. The lipid (fatty) fraction of the biomass can be used to make biodiesel and other liquid fuel substitutes. Microalgal-derived biofuels are currently developed both through heterotrophic cultivation and phototrophic growth. Non-fuel applications for algae include waste water remediation, high value pharmaceuticals, cosmetics and chemicals.	None	Very low	Very low	Very low	5	>2030
	Hydrocarbon excreting micro-organisms (Helioculture)	The cultivation of photosynthetic microorganisms that are circulated in a solution of micronutrients, brackish water and CO_2, which directly excrete hydrocarbons that can be used as fossil fuel substitutes (e.g. ethanol, diesel). The process uses solar energy.	None	None	Very low	Very low	5	>2030
	Nanomaterial catalysts	Conversion of CO_2 and steam into methane and other hydrocarbons. Processes mainly involve the use of complex arrays or reactors being exposed to sunlight, and the use of titanium based nanomaterial catalysts	None	None	None	Very low	3	>2030
	Photocatalytic reduction of CO_2 (CR5)	High temperature solar concentrator provides heat for chemical splitting (decomposition) of CO_2 and H_2O into CO, H_2 and O_2 using catalysis. The CO and H_2 together provide a syngas that can be transformed into multiple hydrocarbon products using the Fischer-Tropsch process. A number of different systems and catalysts are currently being researched (including both metallic and non-metallic). Technologies under development include the Counter Rotating Ring Receiver Reactor Recuperator (CR5).	None	None	None	Very low	5	>2030
	Synthetic methane	In an exothermic reaction between H_2 and CO_2, CH_4 and H_2O are produced. The reaction is usually carried out in the presence of a catalyst. Alternatively, a biological methanation process can be deployed. To be considered low carbon fuel production, the process energy would need to be renewable.	None	Low	Very low	Medium	7-8	2020-2025
	Synthetic methanol	The electrolysis of water produces H_2 which is combined with CO_2, compressed and reacted over a metal/metal oxide catalyst to produce methanol and water. The separated methanol can be directly blended with gasoline for use as a transport fuel. Methanol can be used in a wide range of concentrations mixed with gasoline, from small concentrations where it is an additive up to high concentrations such as the M85 (15%	None	Medium-High	Very low	Medium	8	2020-2025

CCU category	CCU technology	Description	UK demand 2016	UK demand 2030	Global demand 2016	Global demand 2030	Current TRL	Timeframe to reach TRL 9
		gasoline and 85% methanol). To be considered low carbon fuel production, the process energy would need to be renewable.						
Enhanced commodity production	Enhanced geothermal systems with CO_2	Enhanced Geothermal System with CO_2 (EGSCO2) is a variant of "hot rock" geothermal energy systems, and has reported benefits compared to water based systems in that properties of CO_2 (e.g. phase behaviour) reduces the pumping requirements when compared to water-based systems, increasing generation efficiency at the surface, and reducing heat loss in the geothermal reservoir.	None	None	Very low	Medium	5	>2030
	Methanol yield boosting	The yield of methanol from conventional methanol synthesis can be increased (estimated by up to 20%) by the injection of additional CO_2 upstream of the methanol reformer.	None	None	Low	Low	9	<2016
	Supercritical CO_2 power cycles	The use of supercritical CO_2 in closed loop power cycles as a replacement for steam (e.g. in fossil fuel-fired or nuclear power plants). Benefits reportedly include increased electricity conversion efficiency, less thermal fatigue and corrosion.	None	Very low	None	Very low	4-7	>2030
	Urea yield boosting	Urea yield boosting is a well-known application of CO_2 and is used for the production of fertilisers (urea granules and other fertiliser derivatives).	None	None	Medium	Medium	9	<2016
Food & Drink	Beverage carbonation	Captured ("beverage grade") CO_2 may be utilised directly in (soft drink or alcoholic) beverage carbonation.	High	High	Medium	Medium	9	<2016
	Food freezing, chilling and packaging	Captured CO_2 may be utilised directly in food-related applications, such as freezing food using dry ice. In packaging applications, CO_2 is used in modified atmosphere packaging (MAP) with products such as cheese, poultry, snacks, produce and red meat, or in controlled atmosphere packaging (CAP), where food products are packaged in an atmosphere designed to extend shelf life. (See also 'Refrigerant gas' in the 'Other - Industrial applications' category.)	Medium	Medium	High	High	9	<2016
	Horticulture (glasshouses)	Growth rates of several plant species increase with elevated CO_2 levels as long as all other nutrients, water and sunlight are available in abundance. Glasshouses currently employ natural gas CHP systems or boilers, or otherwise technical CO_2. In case of a CHP engine or boiler, CO_2 is collected from the flue gases and distributed inside the greenhouse via diffusers.	Medium	High	Very low	Low	9	<2016
Other - Industrial applications	Electronics	Printed circuit board manufacture uses small quantities of CO_2 in niche applications, predominantly as a cleaning fluid.	Very low	Very low	Very low	Very low	9	<2016

CCU category	CCU technology	Description	UK demand		Global demand		Current TRL	Timeframe to reach TRL 9
			2016	2030	2016	2030		
	Metal working (including casting, moulding and welding)	The mould for CO_2 casting is made of a mixture of sand and liquid silicate binder which is hardened by passing CO_2 gas over the mould. The equipment of the moulding process include CO_2 cylinder, regulator, hoses and hand held applicator gun or nozzle. CO_2 moulding reportedly delivers great accuracy in production. CO_2 is also used in welding as a shrouding gas to prevent oxidation of the weld metal, either as pure CO_2 or otherwise combined with argon or helium.	Low	Low	Low	Low	9	<2016
	Refrigerant gas	CO_2 is used as the working fluid in refrigeration plant, particularly for larger industrial air conditioning and refrigeration systems. It replaces more toxic refrigerant gases that also have significantly greater global warming potential.	Very low	Very low	Very low	Very low	9	<2016
	Supercritical CO_2	Supercritical CO_2 can be utilised in a wide range of applications. These include: Coffee decaffeination, Extraction of aromas or flavours and plant substances, Pharmaceutical processes and as a solvent in dry cleaning. Benefits of using CO_2 compared to other chemicals traditionally used are that it is inert and non-toxic. Furthermore, because of its low critical temperature and moderate pressure requirements, natural substances can be treated particularly gently.	Very low	Very low	Low	Low	9	<2016
	Water treatment and pH control	CO_2 is used for re-mineralisation of water following reverse osmosis and for pH control (reduction). CO_2 can also be used for pH control in swimming pools.	Low	Low	Low	Low	9	<2016

Appendix 2: Stakeholders consulted

Workshop attendees: 14 October 2016

Andy Roberts (UK Petroleum Industry Association)
Benedikt Stefánsson (Carbon Recycling International)
Brian Allison (BEIS)
David Fielder (BEIS)
David Peralta-Solorio (Uniper Technologies)
David Sevier (Carbon Cycle)
Fabricio Marques (CCm Research)
Grant Wilson (University of Sheffield)
Ian Ellerington (BEIS)
Harriet Howe (CCS Association)
Hazel Robertson (Pale Blue Dot)
Louise Macdonell (Scottish Enterprise)
Mark Lewis (Teesside Collective)
Marvin Taylor (BEIS)
Michael Evans (Cambridge Carbon Capture)
Paula Carey (Carbon8)
Richard Hewitt-Jones (Carbon Clean Solutions)
Richard Leese (Mineral Products Association)
Solomon Brown (University of Sheffield on behalf of the IChemE)

Workshop attendees: 5 December 2016

Alex Smith (Chemical Process Industries)
Amy Cutter (BEIS)
Andy Eastlake (LowCVP)
Andy Roberts (UK Petroleum Industry Association)
Angela Whelan (Ecofin)
Brian Allison (BEIS)
Bruce Adderley (UK Carbon Capture and Storage)
Byrony Livesey (Costain)
Chris Bowlas (BP)
Chris Plackett (FEC Energy)
Ian Ellerington (BEIS)
Phil Cohen (BEIS)
David Fielder (BEIS)
David Peralta-Solorio (Uniper Technologies)
David Pilbeam (Pale Blu Dot)
David Sevier (Carbon Cycle)
John Hand (Scottish Enterprise)
Harriet Howe (CCS Association)

Katy Armstrong (University of Sheffield)
Mark Sankey (BP)
Marvin Taylor (BEIS)
Silvia Madeddu (Cambridge Carbon Capture)
Michael Priestnall (Innovate UK)
Paula Carey (Carbon8)
Peter Clark (Innovate UK)
Phil MacDonald (Sandbag)
Phil Pearson (APS Group)
Rebecca Hooper (Mineral Products Association)
Ron Loveland (Wales)
Sarah Tennison (Tees Valley Unlimited)
Stephen Smith (Committee on Climate Change)

Stakeholders consulted: September 2016 – February 2017

Andy Eastlake (LowCVP)
Angela Whelan (Ecofin Foundation)
Ben Bishop (British Sugar)
Benedikt Stefánsson (Carbon Recycling International - CRI)
Chris Plackett (Farm Energy Centre)
David Millward (Air Liquide)
David Sevier (Carbon Cycle)
Derek Hargreaves (Cucumber Growers Association)
Douglas Hoffer (GE Global Research)
Fiona Palmer (British Soft Drinks Association)
Guy Macpherson-Grant (EGS Energy Ltd)
Hermann Pengg (Audi AG)
Hugh Tucker (UK Petroleum Industry Association)
James Coffington (Cornerways nursery)
Jason Shipstone (Drax Power)
Jenni McDonnell (Knowledge Transfer Network)
Jennifer Wagner (Carbon Cure)
Lee Stiles (Lea Valley Growers Association)
Ladan Iravanian (Tata Chemicals Europe)
Marcus Newborough (ITM Power)
Mark Knowles (Liverpool
Mark Lewis (Teesside Collective)
Mark Sceats (Calix)
Martin Forsyth (British Frozen Food Federation)
Matthew Onions (BOC - Linde Group)
Nick van Dijk (ITM Power)
Paula Carey (Carbon 8)
Patrick Lynch/Tom Sullivan (Greenergy)
Phil Morley (British Tomato Growers Association)
Phil Pearson (APS Salads)

Philip Robinson (Chemistry Growth Partnership)
Diana Casey/Rebecca Hooper/Richard Leese (Mineral Products Association)
Rik Ryman (Solidia)
Rowena Sellens (Econic Technologies)
Ryan Law (Geothermal Engineering Ltd)
Stephen Marland (National Grid)
Stephen Reeson (Food & Drink Federation)
Thomas Schlegel (EESAC)

Appendix 3: CCU technology case studies

Carbonation

Case study on carbonation: Carbon8's Accelerated Carbonation Technology (UK)

Carbon8 utilises Accelerated Carbonation Technology (ACT) for the treatment of industrial waste and contaminated soils. The development of ACT is the result of over 15 years of research into waste treatment at the University of Greenwich. ACT can be used in both on-site and off-site operations and can be integrated into existing industrial processes. It is a controlled accelerated version of the naturally occurring carbonation process, which results in an improvement in the chemical and physical properties of the treated materials. The process permanently captures CO_2, which is stored as a carbonate (either $CaCO_3$ or $MgCO_3$).

The process diverts waste from landfill and is a replacement source for natural aggregate. Materials and products generated through the process can be re-used (or disposed of more cheaply), and with significantly shorter treatment times than traditional methods.

The company is currently utilising high purity CO_2 emissions from bioethanol and fertiliser production, supplied by Air Liquide. It has also successfully trialled using flue gases from cement works and combustion of landfill gas. While the ACT process can tolerate CO_2 at different purity levels ranging from 10-90%, 50-60% is considered to be an ideal purity.

Carbon8's business model functions on charging a gate fee for waste treatment and selling the aggregate. Two plants are being operated in Brandon (Suffolk) and Avonmouth, each processing 30 kt/yr APCr (Air Pollution Control residues). These are co-located next to sites operated by Lignacite, a block manufacturer, rather than the waste source. Carbon8 aim to have 5-6 plants in operation by 2021, processing 24 0kt/yr of waste in total. Investment costs are around £5m per plant, and plants can reportedly be commissioned in less than 6 months. Other future applications of the technology are the treatment of steel slags or cement dust. Carbon8's principal investor is Grundon Waste Management.

One barrier to this growth plan is that it may be challenging to find sufficient material to process as it is currently under contract with waste companies. In addition, current local/national planning policy restricts the plant capacity to 30 kt/yr (above this capacity the planning decision falls under the National Strategic Planning legislation which has an implication on both the cost and timeline of the process). A further challenge Carbon8 faces is the EU End of Waste Regulations,[174] which have to be met if the end-product can be sold into the block market. As a result, the Environment Agency does not allow Carbon8 to market products that are made from certain waste streams.

[174] https://www.gov.uk/guidance/turn-your-waste-into-a-new-non-waste-product-or-material

Horticulture

Case study for horticulture: British Sugar / Cornerways Nursery (UK)

CO_2 is captured from the flue gas of British Sugar's Wissington sugar refinery's CHP plant and piped directly into the Cornerways tomato nursery (Cornerways is wholly owned by British Sugar). The nursery consumes between 5-10 ktCO_2/yr. Hot water is also exported from the plant around the glasshouse through a network of more than 240 miles of piping. This process extends the growing season to range from February to November and furthermore increases crop yield. The site also harvests the rainwater from the glasshouse roof; over 115 million litres are collected annually to irrigate the plants.

The 18 ha nursery in Norfolk was purpose built and benefits from being located only 500 m away from the sugar refinery. It has been operational since 2000 and was built in stages, the last expansion taking place in 2010. More than £15m has been invested in the nursery to date. The Wissington refinery is well suited to provide CO_2 and heat as it operates continuously throughout the year, unlike British Sugar's other facilities.

In October 2016, British Sugars announced that the Cornerways Nursery will no longer produce tomatoes after the current crop. From 2017, the glasshouse is now used to grow medicinal cannabis for use in the pharmaceutical sector. CO_2 will still be utilised.

Case study for horticulture: OCAP (Netherlands)

The OCAP (Organic CO_2 for assimilation by plants) concept was set up in 2005 by VolkerWessels and Linde Gas Benelux and since 2013 has been operated by Linde. OCAP delivers CO_2 to greenhouses located between Rotterdam and Amsterdam. The CO_2 gas originates from two high quality sources. One of these sources is a hydrogen production facility that is part of the Shell Pernis Oil Refinery; this facility emits a pure stream of CO_2 as a by-product of the hydrogen production process. The other source, the Abengoa Bioenergy plant, produces CO_2 as a by-product from bioethanol production. In addition to supplying greenhouses, a further but substantially smaller part of the captured CO_2 is liquefied by Linde year-round and sold primarily to the food industry

OCAP makes use of an 85 km existing pipeline that was used to transport oil between Rotterdam and Amsterdam, but was out of service for 25 years. The use of this existing transport pipeline enabled OCAP to greatly reduce projects costs. OCAP still had to build a distribution network of approximately 300 km of smaller pipes running to the individual greenhouses. Currently about 400 ktCO_2/yr is delivered to more than 580 greenhouses via a 97 km transport pipeline and a distribution network of approximately 200 km. These glasshouses cover approximately 2,000 ha production area or 20% of total national production area. According to OCAP, the re-use of 400 ktCO_2 by OCAP avoids the combustion of 115 million m^3 of natural gas and avoids the emission of 205 ktCO_2/yr.

Polymer processing

Case study for polymer processing: Covestro's Dream Project for CO_2 to plastics (Germany)

Covestro is a spinout, formed in 2015 from Bayer Material Science, which has developed a process for using CO_2 to produce polyether polycarbonate polyols (PPP) suitable for use by the polyurethane industry. In 2016, the company inaugurated its CO_2-to-polyols plant in Dormagen, Germany and is expected to produce 5 t/yr of PPP. Prior to this, Bayer was operating a pilot scale facility at Leverkusen. The pilot plant was used to test the robustness of the zinc based catalyst and the reaction process to various qualities of CO_2 and propylene oxide levels.

CO_2 is used to replace between 15-25% of the epoxide raw material conventionally used in polyol production. The company has also opened a production plant for an innovative foam component made with 20% CO_2 at its Dormagen site near Cologne, which involved an investment of €15m. The new process saves a proportional amount of the traditional oil-based raw material. Covestro has received substantial investment and support (reportedly around €118m) from the German authorities over a period of many years.

Synthetic methane

Case study for synthetic methane: Audi e-gas (Germany)

Audi AG operates the world's largest synthetic methane plant in Wertle, Lower Saxony, Germany. The plant capacity is 6.3 MW input power with a plant conversion efficiency of approximately 54%. It was built by ETOGAS, a Stuttgart based plant manufacturer. The plant receives electricity from a wind farm and has been feeding synthetic gas into the natural gas distribution network since 2013. The plant produces 1 kt/yr of methane (Audi e-gas) using 2.8 kt of CO_2. The CO_2 is obtained from an exhaust flow of a bio-methane plant in the immediate vicinity which is operated by an energy utility. The plant uses the **catalytic methanation** process.

Since February, 2016 the Viessmann group has partnered with Audi and is producing synthetic methane at a pilot facility in Allendorf, Hesse. This is the first power-to-gas plant in Germany to utilise the **biological methanation** process to produce synthetic methane on an industrial scale. The CO_2 used in the process reportedly does not need to be present in high concentration or purified form. As such, unrefined biomethane from anaerobic digestion plants can also be used as CO_2 source. Audi-e gas, just like fossil natural gas, can be used as a fuel for combustion engines. The company aims to use this gas to power 1,500 Audi A3 Sportback g-tron vehicles 15,000 km every year.

Synthetic methanol

Case study of synthetic methanol: Carbon Recycling International (Iceland)

Carbon Recycling International (CRI) has developed a process that uses CO_2 and H_2 to produce synthetic methanol through catalytic synthesis. The CO_2 used in the process can be captured from industrial point sources, but must be 99% pure at the inlet to the reactor and free from major impurities which can damage the catalyst. The H_2 can be produced through electrolysis, or using surplus or stranded H_2 from industry.

CRI's George Olah Renewable Methanol Plant located in Svartsengi, Iceland was completed in 2012. All energy used in the plant comes from the Icelandic grid, which is generated from hydro and geothermal energy. CO_2 is captured from the flue gas released by a geothermal power plant located next to the CRI facility. In 2015, CRI expanded the capacity from 1.3 to 5 million litres, equivalent to 4 kt/yr. The plant utilises around 6 ktCO_2/yr. The company has overall ambitions to develop commercial scale plants of 63 billion litres per year, or 50 kt/yr capacity (utilising 72.5 ktCO_2/yr). CRI is developing further pilot scale projects (MefCO2 and FReSMe) with the support of two grants under Horizon 2020. These projects are intended to demonstrate specific potential applications of the technology. Specifically, the use of battery storage in power to fuels production (MefCO2) and how residual blast furnace gases from steel manufacturing can be utilised in the production of synthetic methanol (FReSMe).

The process required ten years of venture capital-financed R&D and engineering to develop the catalyst, CO_2 capture at kiloton scale and pressurised water electrolysis at MW scale. CRI have received from other companies seeking collaborations. In 2013, Methanex (Canada) announced a $5m investment in CRI, and more recently in 2015, the Chinese car manufacturer Geely Auto announced plans to invest $45.5m in CRI over a 3 year period. Geely and CRI intend to collaborate in the deployment of synthetic methanol fuel production technology in China and explore the development and deployment of 100% methanol-fuelled vehicles, with China and Iceland initial target countries. Customers of CRI include Perstorp, a major Scandinavian biodiesel producer, which signed a long-term off-take agreement with CRI in 2015 to use synthetic methanol produced for the production of biodiesel.

Appendix 4: Key emission sources and CCU locations

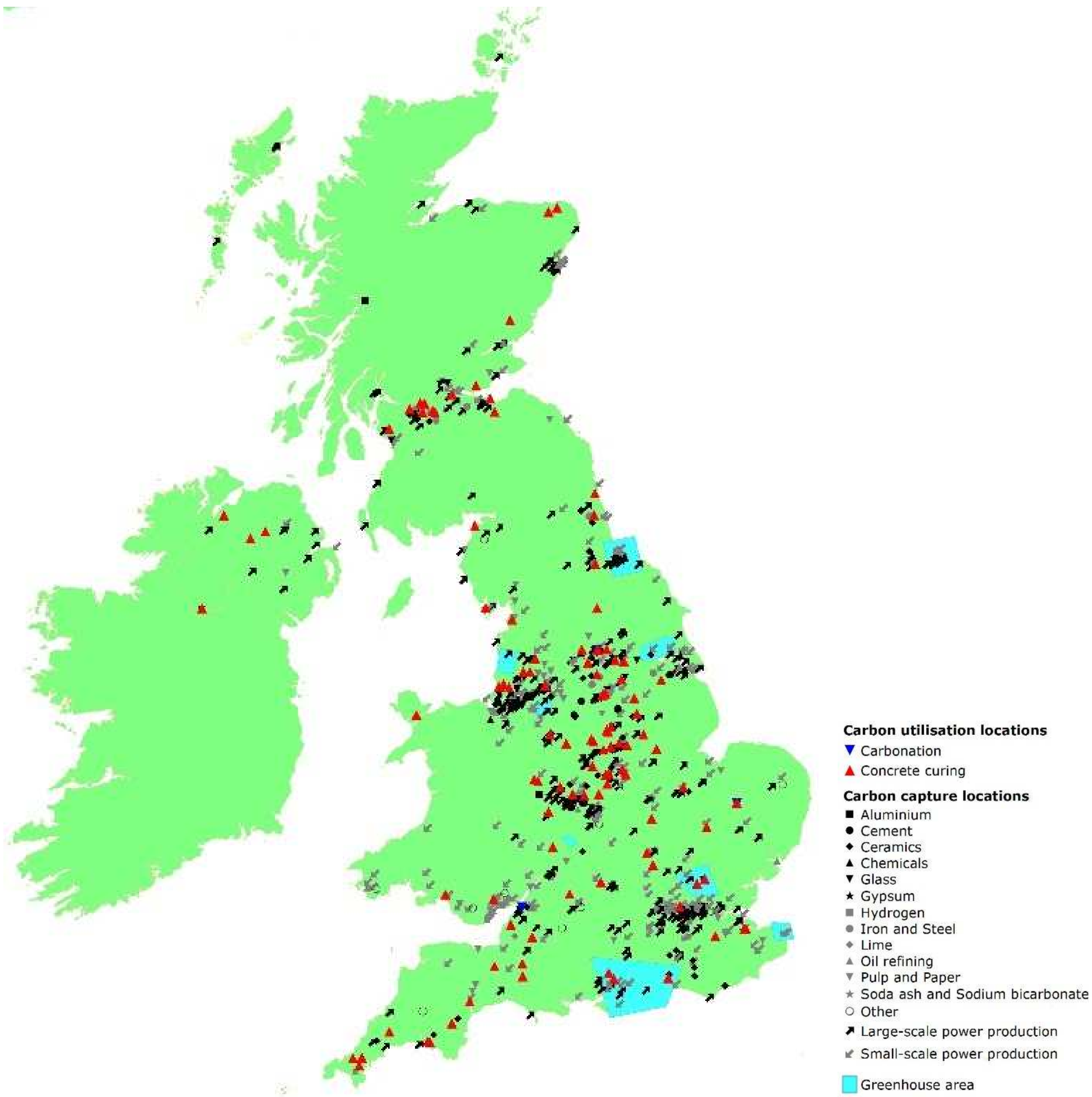

Figure 12. Map showing key emission sources, existing locations for carbonation of waste (APCr), potential future locations concrete curing and the main glasshouse regions in the UK (shaded in green).

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