Implications of the Reuse of Captured CO$_2$ for European Climate Action Policies

Final report
Implications of the Reuse of Captured CO$_2$ for European Climate Action Policies

Final report

By: Chris Hendriks, Paul Noothout (Ecofys), Paul Zakkour and Greg Cook (Carbon Counts)
Date: 20 February 2013

Project number: CLIMA.C.1/SER/2011/0033
ECUNL11593

© Ecofys 2013 by order of: DG Climate Action
Table of contents

Abstract 1

Introduction 5

Part 1: OVERVIEW OF CCU TECHNOLOGIES 7

1 Introduction 9

2 What is CO₂ reuse? 11

3 Why is CCU of interest? 15

4 About CCU technologies 17
   4.1 What are the main technologies involved with CO₂ reuse? 17
   4.2 What is their current status? 21
   4.3 Who is involved in their development? 23
   4.4 Are there any environmental, health or safety issues associated with their development? 26

5 What are the economic factors involved in CO₂ reuse? 29
   5.1 Creating value from products and services 30
   5.2 What is the market demand for CCU? 32
   5.3 What are the costs of CCU technologies? 34
   5.4 Overcoming barriers to commercialisation 36
   5.5 Europe 41
   5.6 Rest of the world 42

6 What could CCU technologies offer for various EU policy considerations? 45
   6.1 CCU and EU Climate Policy 45
   6.1.1 CCU reducing emissions 45
   6.1.2 CCU supporting CCS 48
   6.2 CCU enhancing energy security 50
   6.3 CCU supporting industrial innovation 51

Part 2: TAKING ACTION TO SUPPORT CO₂ REUSE 53

1 Introduction 55

2 Needs for and barriers to CCU development 57
2.1 Innovation analysis framework 57
2.2 Selection of CCU technologies for in-depth analysis 59
2.3 Innovation assessment to CCU needs, barriers and drivers 63
2.3.1 Renewable methanol 63
2.3.2 Formic acid production 64
2.3.3 Algae cultivation 65
2.3.4 Cement production 65
2.3.5 Carbonate mineralisation (other) 66
2.3.6 Polymer processing 67
2.4 General findings 68

3 Opportunities for supporting CCU technologies 71
3.1 Push and pull policy instruments 71
3.2 EU support for innovation in CCU 73
3.2.1 Horizon 2020 – EU Framework Programme for Research and Innovation 73
3.2.2 Technology prizes 77
3.2.3 Knowledge and innovation communities 77
3.2.4 CCU stimulation measures synchronised with existing innovation measures 78
3.3 Implications of the stimulation of CCU technologies on European Policy framework 79
3.3.1 Implications on existing policies 80
3.4 Overview of implications of existing policies on the development of CCU technologies 83

4 Building a long-term strategy for CCU in the European Union 87

Bibliography 91

Annex A – Interviews and survey questions 97
  Interview questionnaire 97
  Online questionnaire 99

Annex B – Selection criteria CCU technologies 101
  Uptake potential 101
  Economic potential 101
  Applicability to the EU 102
  Potential for GHG abatement 102
  Environment, health & safety considerations 102
  Alignment with EU energy policy 103

Annex C – Technology overviews 105
  Renewable methanol 106
  Formic acid production 108
  Algae cultivation 112
  Carbonate mineralisation (other) 119
Polymer processing

Annex D – Communication and CO₂ reuse workshop

Website 133
Workshop 135
Technical sessions with sector experts 135
Panel discussion 138
Results and conclusions 140
Workshop programme 141

Annex E – Overview CO₂ reuse activities 143
Abstract

Until recently, the reuse of CO₂ – or CO₂ utilisation (CCU) - has received limited attention by researchers and policy-makers alike, but new initiatives, publications, ongoing research and demonstration projects point toward new opportunities in the field. Most of the CCU technologies are still in their infancy and for some it will likely take decades to get deployed at any sort of scale. Given the potential benefits offered by CCU technologies - such as emission reductions, energy security, and industrial innovation - and the growing research interest, it is timely to consider policy options to accelerate research, demonstration and deployment (RD&D) of CCU technologies.

This requires a clearer understanding of the range of CCU technologies and their potential impact on climate, energy security and innovation. Aspects such as the current development status and technological development trajectory of the range of CCU technologies are all necessary to help better inform policy decisions. Important questions include: what is CO₂ reuse; why is CO₂ reuse interesting; and what are the potential and economics of the various technological options.

Whilst there is growing interest in technologies that utilise CO₂, this encompasses a wide range of different applications. In the broadest sense, CCU can involve technologies that use CO₂ in the synthesis of new products or as a solvent or working fluid for various processes. We looked at five categories of CCU which cover most of the technologies: CO₂ to fuels; Enhanced commodity production; Enhanced hydrocarbon recovery; CO₂ mineralisation; and Chemicals production.

Globally the current volume of CO₂ utilisation is estimated at about 80 Mt per year, of which most is used in the production of urea (50 Mt). The full potential of CCU is unclear as most of the CCU technologies are in early stage of development and neither their potential nor their cost-effectiveness and impact on CO₂ emission reduction are well-known. Analysis presented in the report suggests that regional or potential in a country for various CCU technologies depends on factors such as geographical or geological conditions (e.g. potential to enhance hydrocarbon recovery) or to industrial development status (e.g. presence of advanced and innovation driven industry).

CCU and EU policy targets
To determine the type of R&D support policies that could be useful for CCU, a good understanding of the extent to which CCU technologies can contribute to existing EU policies is required. Policy areas that can be impacted by CCU could relate to climate action, energy security and industrial innovation. Where a particular technology holds potential to contribute to one or more policy goals, it will likely be necessary to support its development through policy interventions so that they may progress through the development cycle.

The development of CCU technologies faces a number of challenges and barriers. Many CCU technologies are on the brink of the ‘valley of death’, i.e. opportunities need to be provided to translate knowledge via technology development and pilot/demo projects into competitive
manufactured products. The development will depend on significant investments from industrial organisations and thus their willingness to take risk. This requires sufficient trust in the commercial success of the product or technology. Market developments and competitiveness influenced by (future) cost-price of CCU products (including the costs for CO₂ capture) are important factors here. Also in the more fundamental development of the technology challenges are still remaining like the development of catalysts to enhance the conversion rate of CO₂.

Policies to support CCU must be designed carefully to create maximum benefit for reaching the policy objective(s). As stated, the actual benefits of CCU technologies are very unclear and more clarity is needed to what extent the CCU technology contributes to EU policy objectives. By using commonly agreed and approved methodologies to assess factors as the contribution of CCU technologies to environmental improvements (e.g. emission reduction), to economic development (e.g. impact on innovation, industrial competitiveness and deployment) and to energy supply (e.g. improving security of supply), a better understanding can be obtained.

**Policy instruments**
The Commission has the capacity to intervene in the market through development of policies which either "push" development by supporting RD&D, or "pull" instruments involving the creation of measures to drive innovation on a financial and market driven basis.

A main EU push instrument is the EU Framework Programmes. The coming Framework Programme for Research and Innovation Horizon 2020 will run from 2014 to 2020. Horizon 2020 comprises three thematic priorities to which CCU potentially can contribute; Excellent Science, Industrial Leadership and Societal Challenges. Although individual CCU technologies have received financial support in Framework Programme 7 (2007-2013) CCU was not indicated as a specific research area – in contrast to for instance carbon capture and storage. Creating a specific research area for CCU under Horizon 2020 would increase visibility and opportunities for research and innovation in CCU. Such status would improve the opportunities for financing giving a positive impulse to the development of CCU technologies. It should be noted, that due to the heterogeneous character of the CCU research field, defining the scope of funding in this field could be challenging.

Next to subsidies for proposals, innovation can also be driven by instruments like Technology Prizes. Such an instrument is most appropriate for a diverse group of technologies addressing multiple policy targets. The relative benefits of the various CCU technologies are, however, unclear and it is therefore risky to pick winners for dedicated research support. In that respect, CCU would be an appropriate research area for a prize concept to ‘discover’ the best option. In the prize concept the financial reward goes to the innovators who come up with the best working solutions instead of proposals. It is an instrument that allows for selecting the best technology based on pre-set criteria, instead of supporting unproven technologies from the start. At the other hand, prize competition tends to overlook basic research and intellectual property rights are not always clear.
Another potential interesting initiative for CCU is the EU innovation centres, such as the Knowledge and Innovation Communities (KIC). For CCU relevant KIC institutes are Climate-KIC and KIC-InnoEnergy.

Besides supporting “push” policies, “pull” policies will be required as well. Technology (or market) pull is necessary in providing clear signals to market participants that production processes and products are eligible under EU and Member State law, and to remove potential obstacles in current policies that could inhibit deployment. This will help to “pull” technologies from demonstration into mature commercial markets. There are few existing EU policies that have direct impact on CCU technology development and deployment from a market perspective. The most prominent is the EU-ETS. Others relate to the Renewable Energy Directive and Fuel Quality Directive and product standards, e.g. cement blending rates.

- Within the EU-ETS, presently, technologies delivering temporary storage of CO$_2$ cannot be accounted for as not-emitted. Also transferring CO$_2$ to installations outside the ETS does not qualify and need to be accounted for, i.e. one is obliged to surrender emission allowances for the transferred CO$_2$. Nevertheless, there is scope for changes in this requirement as it is suggested that this development should not “...exclude future innovations”. This may potentially open the possible to opt-in of new activities/technologies such as CCU. Under Art. 24 of the ETS Directive, subject to the submission of appropriate MRGs – this would take place through a comitology process under Art. 23 of the ETS Directive.

- Standards for products may have (unintended) effect on the applicability of CCU products. An example is the cement blending rate requirements. Within the EU, European Standard EN197-1 sets limits on the rates at which various products may be blended for different types of cements. This could potentially affect the market of cement products produced through CO$_2$ mineralisation.

- Renewable methanol (not based on biomass) can be eligible under the Renewable Energy Directive only when 100% obtained from renewable energy sources. Interpretation of the Directive resulted that grid-connected installations could not qualify when non-renewables were part of the grid. In practise this will hamper the uptake of this technology.

The CCU field is heterogeneous, covering wide range of technologies and products, and a wide range of new and diverse actors and industries. It may be useful if the various communities could continue dialogue at an EU level, drawing in the commonalities of interests (e.g. production of chemicals, mineralisation, fuel production). Regular meetings to discuss research and development opportunities and policy complications could help solidify the views of the sector, and facilitate a common language and understanding of research and policy needs in the field of CCU. Nevertheless, discussion platforms like a (technology) platform, dedicated events or regular meetings need to be arranged so that the interest of CCU can be guarded and it can act as contact point for the Europe Commission.
Introduction

In accordance with the requirements of the consortium's contract with the DG Climate Action ("DG Clima"), this report sets out the findings of analysis carried out on carbon dioxide (CO₂) reuse technologies.

The content of the report takes account of the obligations of the project consortium as set out in our Proposal and agreed in the Inception Report. Furthermore, it is based on reflections on the informal workshop held with various key stakeholders in Brussels on 30 May 2012 and the CO₂ reuse workshop of 24 October 2012.

The report is set out as follows:

**Part 1 – Overview of CO₂ reuse.** This part is designed to outline the main features of CCU technologies and to provide sufficient background to the topic of CO₂ reuse for policy-makers. It includes context description, technology overview and possible impact of CCU technology on EU policy objectives. It draws on a review of relevant literature and also from the diversity of views and questions posed by key stakeholders such as staff from other DGs and Member States. From these, it was apparent to the project team that there is a need for a policy-guide outlining issues. On this basis, we have prepared a description of CO₂ reuse below with the objective of creating a guidance document which can be used to better inform stakeholders about its potential.

**Part 2 – Taking action to support CO₂ reuse.** This part of the report addresses more specific EU-related aspects associated with CCU technologies, including an evaluation of the political case for supporting CO₂ reuse in the European Union (EU), potential policy interventions to support CCU technologies, and potential implications of such support. The objective of this part of the report is to provide the DG Clima with a structured appraisal of whether and how to support CO₂ reuse in the EU. This Part focuses on the identifying actions to stimulate CCU technologies, types of policy measure available to stimulate CCU technologies and how such measures align with existing EU policy on energy, climate and industrial innovation.
Part 1:
OVERVIEW OF CCU TECHNOLOGIES
1 Introduction

CO₂ reuse is being applied for many years in some industrial sectors, e.g. oil exploration and the chemical industry. Nevertheless still not much is known about the research field ‘CO₂ reuse’. Common questions surrounding CO₂ reuse technologies are: what is CO₂ reuse technology? Why is it of interest? Where can CO₂ reuse be useful?

To answer these questions, the project team has undertaken a wide ranging literature review including several research reports, press releases and trade articles on emergent CO₂ reuse applications and technologies. Based on the review, it is apparent that the existing literature has tended to present a wide array of CCU technologies with technical descriptions on each, alongside some other economic and environmental considerations. In order to present the issues in a policy relevant way inside the European Commission (EC), it will be important to present the findings according to several policy-oriented issues, as opposed to taking a technology-oriented approach as adopted in the existing literature (i.e. structuring the report around key policy questions as opposed to different types of technologies). This, in our opinion, provides a more valuable addition to the literature on this topic, and in turn assists DG Clima in outreach to other DGs and policy-makers in Member States in helping to build a better understanding of what CO₂ reuse involves, and developing ideas regarding whether there is a case for further action.
2 What is CO₂ reuse?

Over the last decade there has been increasing interest in the role that carbon dioxide capture and geological storage – referred to as "CCS" – can play in reducing emissions from energy and industrial related sources. Less attention has been given to the role that reusing captured CO₂ – or CO₂ utilisation (CCU)¹ – could play in mitigating climate change. More recently interest has begun to grow due to a variety of reasons, such as the potential for CCU to reduce emissions of greenhouse gases (GHGs) to the atmosphere and the scope for it to offset some of the costs of CCS.

However, CCU technologies differ from CCS as geological storage is not an objective, or at least not the primary objective – although CCU could help to support CCS deployment. Rather, CCU is a broad term which applies to a range of applications that can utilise CO₂, either as part of a conversion process, i.e. for the fabrication or synthesis of new products (e.g. to make polymers in the chemical sector), or in non-conversion processes, where CO₂ acts a solvent or working fluid (e.g. for enhanced oil recovery; CO₂-EOR). This typology, as presented graphically in Figure 1, has provided the basis for the research undertaken in this report, and the following working definition of CCU has been adopted:

'Carbon dioxide utilisation (CCU) covers a broad range of processes involving the separation of carbon dioxide (CO₂) from industrial and energy related sources (where necessary), its transport (where necessary), and its use in the fabrication or synthesis of new products or as a solvent or working fluid for various industrial processes.'

This working definition, whilst somewhat simplistic, draws on that typically applied to CCS, ² but does potentially mask the wide variety or potential applications involving CCU. Other attempts have made to characterise CCU in various ways, including as ‘...a process whereby the CO₂ molecule ends up as a new molecule’ (Styring et al., 2011) or as means to '...generate revenue that can partially offset the cost of CO₂ capture, as a transitional measure to assist the accelerated uptake of CCS' (MEF, 2009; Parsons Brinckerhoff/GCCSI, 2011). The research presented in this paper considers technologies which achieve both objectives.

Notwithstanding the diverse range of potential applications, and resultant challenge in characterising CCU, a unifying feature of all CCU technologies is that they have some capacity to retain carbon

---

¹ The term CO₂ utilisation rather than CO₂ reuse is used in this report. The principle reason for this is one of interpretation: CO₂ that is being used in the various applications under consideration is typically a by-product resulting from the oxidation solid, liquid or gaseous fossil fuels. In this context, it is conceivable that the term "reuse" could be applied, because some definitions of 'waste' include by-products within their scope, and the waste hierarchy suggests that reuse is the second preferred choice for such wastes (i.e. reduce, reuse, recycle); however, the term "reuse" in a pure sense implies that the CO₂ has already been used and is being used again, whereas the CO₂ under consideration within this report in most cases didn’t have a previous use. For this reason the term CO₂ reuse is considered misleading, hence the use of the term CO₂ utilisation as fairer reflection of the scope of this research.

² For example, in the 2005 IPCC Special Report on Carbon Dioxide Capture and Storage (Metz et al.), and as applied for CCS in the EU's Directive on geological storage of CO₂.
within a cycle at least over the short-term, thus avoiding release of CO$_2$ to the atmosphere (Styring et al., 2011). Different technologies have different potential to achieve this objective; for some the removal is permanent, with the carbon from CO$_2$ ending up locked up in minerals or in long-lasting products (e.g. some polymers), or stored indefinitely in geological formations (e.g. in enhanced oil recovery); for others e.g. where the carbon is converted to fuels, removal is only temporary and therefore offers only limited potential to abate CO$_2$ emissions. In the case of the latter, air capture would be needed to close the carbon cycle again (Styring et al., 2011). But also in many such cases CCU can deliver secondary benefits which can lead to reductions in GHG emissions outside the immediate scope of the activity (sometimes referred to as "leakage effects"). Examples include improvements to process efficiency, which leads to increases in energy efficiency therefore reducing fossil fuel consumption for the same end service (e.g. enhanced power cycles using supercritical CO$_2$), the displacement of more intensive forms of production of intermediates within a value chain (e.g. in bulk chemicals production), or through substitution of conventional fossil fuels (e.g. in algae-based biofuels production systems using CO$_2$).

Additionally, CCU is widely viewed as a suite of technologies that can provide support for CCS deployment, by creating additional revenues that can partially offset the costs of establishing a CCS chain (i.e. the chain of capture, transport, injection and storage). In such cases, it is important to distinguish between the use of captive and non-captive sources of CO$_2$; in the case of the former, utilisation of CO$_2$ produced onsite – particularly a high purity source – is unlikely to offer much potential for this type of support, whereas applications involving transport of CO$_2$ from one location to another can potentially act as a precursor for a CCS value chain.
Various CCU technologies – as described in subsequent sections of this report – also potentially offer other forms of economic and environmental benefits, which can help to further drive interest in CCU as a means to support other strands of EU policy such as innovation and energy security, as well as climate protection objectives.

More problematically, one of the main challenges for CCU uptake is the low reactive state of CO$_2$ under standard conditions, meaning that its utilisation presents an energy trade off and/or a reduction in its activation energy requirement for reactions through the use of catalysts (Styring et al., 2011). This means that the conditions under which CCU could apply may tend towards niche applications where there is sufficient surplus energy – generated from renewable sources – and/or where substitution of the conventional production method leads to energy or materials gains during fabrication/synthesis. As a result, there are some geographical factors to consider when assessing the potential for CCU within a diverse region such as the EU. Another major challenge is how much CO$_2$ might be required for the range of applications; for CCU to make an impact on CO$_2$ emissions in the EU, the applications most offer reasonable potential for large scale CO$_2$ utilisation.

CCU technologies also present potential challenges to policy creation and regulatory enforcement. The way in which CO$_2$ is used in many CCU applications, and in particular the temporal aspects of emission abatement described previously, mean that policies which support CCU must be designed carefully in order that the maximum benefit for the policy objective is achieved; it may be difficult to justify the provision of carbon price incentives to CCU technologies which only offer short-term storage of CO$_2$ rather than long-term – or permanent – emission reductions. Similarly, where the potential for a reversal in carbon storage exists e.g. through release or oxidation of the carbon stored in a product, or where secondary benefits are difficult to measure, quantify and attribute to a particular activity, incentives will be difficult to design effectively and enforcement of monitoring, reporting and verification will be equally challenging.

As such, CCU presents an extremely novel and challenging issue to consider for policy-makers. The following sections of this report attempt to provide some insight into all of the issues highlighted. The complexity and novelty of the subject means that the review provided is unlikely to be exhaustive. However, the range of issue touched upon in subsequent sections is likely to be applicable to most potential applications of CCU.
3 Why is CCU of interest?

The previous section highlighted many potential benefits of CCU, and also some of the potential issues that will need to be addressed. But it is important to note that using CO₂ as a product is not a new practice. Its use for enhanced oil recovery (CO₂-EOR) has been applied since the early 1970s, with over 50 MtCO₂ per year currently being injected into mature oil reservoirs for such purposes in the United States and elsewhere. Further, CO₂ produced during the manufacture of hydrogen for conversion to ammonia has also been widely used to synthesize urea in the inorganic fertiliser industry for many years. In some cases, the fertiliser plant also captures supplemental CO₂ from onsite boilers and other sources to provide an additional source of carbon. Presently around 120 MtCO₂ is used in this way around the world (Zakkour and Cook, 2010). Smaller-scale applications of CO₂ use include in greenhouses (to enhance plant growth), use as a fire retardant (in fire extinguishers) and in beverage carbonation and food production, where, for the latter, supercritical CO₂ can act as an excellent solvent for removing organic substances (e.g. in the decaffeination of coffee, decontamination of grain or for dry cleaning). Typically these processes utilise either natural sources of CO₂ (approximately 85% of the CO₂ used for EOR in the United States), manufacture it from the burning of natural gas (e.g. in greenhouse heaters), or capture it from anthropogenic sources where industrial processes produce CO₂ of a fairly high-purity (e.g. steam methane reforming or gas processing).

However, the overall demand for CO₂ in such applications (probably <250 MCO₂/year worldwide) relative to the scale of CO₂ emissions worldwide – more than 30 GtCO₂ in 2010 (US DOE, 2012) – has meant that interest in the application of CCU technologies for the purpose of emissions abatement has been limited. More recently though, perceptions have begun to change in many regions of the world, with a diverse range of reasons driving interest including:

- Emergence of new techniques that have the potential to reduce emissions of CO₂ to the atmosphere by capturing and converting it into high value products such as speciality chemicals (e.g. polyurethane and polycarbonate). Research and pilot projects are ongoing in many jurisdictions, including in Germany, UK, and the US;
- Increasing concerns over the cost of establishing CCS value chains and the potential for CCU applications to provide a means to partially offset the costs involved. Although political and commercial interest in CCS took off rapidly from around 2005 onwards, more recently the global financial crisis, increasing uncertainty about long-term international commitments to climate change after 2012, and several false starts for CCS projects has tempered views on the potential of the technology. CCU offers a potential means to reignite interest;
- Lack of geological storage potential for CCS (e.g. Finland, Estonia) or public concerns over the safety, viability and need for CCS in some jurisdictions (e.g. in Germany). In these contexts,

---

3 See, for example: UNIDO (2011), as well as other sources.
CCU technologies can offer an alternative route through which to mobilise investment into CO₂ capture and transport;

- Realisation that CCU technologies can offer a range of means to enhance energy security. Methods such as enhanced oil recovery using CO₂ (CO₂-EOR) can maximise and extend the life of national hydrocarbon assets in oil producing provinces, such as the North Sea, as well as offering a means to lock-up CO₂ in geological formations. Alternatively, combining CCU technologies such as renewable methanol or formic acid production with baseload renewable energy generation technologies – such as offshore wind or geothermal energy – offers a means to convert energy into a stored form during off-peak time;

- The suite of technologies involved in using CO₂ offer a range of opportunities for industrial innovation, potentially creating means for national economies and commercial companies to increase their competitiveness, as well as increasing the sustainability of industrial practices.

With these drivers in mind, the following sections consider the range of CCU applications, their status, the actors involved in their development, and a more detailed review of the economic, environmental, policy and regulatory aspects associated with CCU.
4 About CCU technologies

4.1 What are the main technologies involved with CO\textsubscript{2} reuse?

Brief technical descriptions of the range of CCU technologies considered within the scope of this report are outlined below (Table 1). In presenting the technologies, a classification around five groups of end-use applications has been used. Classification was required in order to simplify the way in which the diverse range of CCU applications may be considered. The scheme used is developed on the basis of sectors in which the technologies could apply, rather than the means by which they are applied i.e. in a functional rather than technical grouping. A sectoral approach was taken as it affords an easier assessment of the range of policy, economic and regulatory issues associated with each group of technologies, and potentially allows common means of addressing policy issues for each group to be assessed. The groups developed are:

- **CO\textsubscript{2} to fuels** – 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. renewable methanol), and more embryonic forms of energy carrier development (e.g. biofuels from algae).

- **Enhanced commodity production** – this group of technologies involve using CO\textsubscript{2} to boost production of certain goods, typically where CO\textsubscript{2} is already used but could be modified (e.g. urea yield boosting). It also includes using CO\textsubscript{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\textsubscript{2}.

- **Enhanced hydrocarbon production** – this group of technologies involve using CO\textsubscript{2} as a working fluid to increase recovery of hydrocarbons from the subsurface (e.g. CO\textsubscript{2}-EOR). They range in maturity from commercially viable under certain conditions through to pilot phase;

- **CO\textsubscript{2} mineralisation** – this group of technologies relies on the accelerated chemical weathering of certain minerals using CO\textsubscript{2}. It can be used in a range of applications, typically involving construction materials (e.g. concrete curing) or in niche circumstances such as mine tailing stabilisation;

- **Chemicals production** – CO\textsubscript{2} can be used in the synthesis of a range of intermediates for use in chemical and pharmaceuticals production, including carbamates, carboxylation, insertion reactions, inorganic complexes and polymer production. Conversion methods require the use of catalysts, heat and/or pressure to break the stable CO\textsubscript{2} structure, and include photocatalysis or electrochemical reduction. One of the most promising technologies is the use of CO\textsubscript{2} to make various polymers such as polycarbonate.

Further simplification has also been used within each group, narrowing the range of applications down to fifteen. This is a simplified view of the vast potential range of applications, particularly in the chemicals production group. An excellent overview of the range of potential CCU applications in chemicals production has been compiled by Styring et al. (2011).
Within these groupings, some of the technologies offer incremental means to improve production of existing operations (e.g. enhanced commodity production, enhanced hydrocarbon production, CO₂ mineralisation), whilst others more wholesale or step-change technologies for producing certain products (e.g. CO₂ to fuels, certain chemical production processes). As such, conceivably the incremental measures could potentially be readily taken up into existing value chains, while for others, new production methods and new value chains will be needed. This has implications for the design of policy measures that may be used to support research, demonstration or wider development of the various technologies.
### Table 1 - Summary of main CCU technologies reviewed

<table>
<thead>
<tr>
<th>CCU category</th>
<th>Brief technology description</th>
</tr>
</thead>
</table>
| CO₂ to fuels | This group includes technologies involving chemical processes (e.g. H₂ production) or intermediates that can be used to generate H₂ (e.g. formic acid). Others are dependent on biological or physical processes to produce hydrogen carrying products.  
  - **Hydrogen** – these involve reductive process such as the production of H₂ via electrolysis of water using renewable energy, and its reaction over a metal/metal oxide catalyst to produce methanol, the latter element being a standard process for making methanol, in use for almost 50 years. Electrochemical reduction of CO₂ and water can also be used to produce formic acid, which can be used as a H₂ carrier in batteries/fuel cells, and is subject to R&D in a number of areas.  
  - **Algae (for biofuels/biomass)** – these involve algae cultivation using nutrient-rich, typically saline or brackish water in open ponds or closed bioreactors, where CO₂ 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. Another strand of R&D involves cultivation of photosynthetic microorganisms using solar energy and CO₂, which can directly excrete hydrocarbons that can be used as fossil fuel substitutes (e.g. ethanol; see Joule® of Massachusetts, US).  
  - **Photocatalytic processes** – these generally involve the decomposition of CO₂ using solar energy and catalysts, to produce syngas which can be converted to fuels using Fischer-Tropsch reactions. A number of different systems and catalysts are currently being researched. Technologies under development include the Counter Rotating Ring Receiver Reactor Recuperator (CR5) & photocatalytic reduction of CO₂ (gallium-phosphide & graphitic carbon nitride).  
  - **Nanomaterial catalysts** – under development which can convert CO₂ 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 (TiO₂) based nanomaterials. |
| Enhanced commodity production | Several technologies involving CO₂ use can boost the production of certain commodities. These include physical-based systems using CO₂ as a working fluid to improve power generation cycles, and chemical-based processes which increase production of intermediates.  
  - **Power cycles** – in these systems, CO₂ is used as a substitute water as a working fluid. Enhanced Geothermal System with CO₂ (EGSCO₂) is a variant of “hot rock” geothermal energy systems, and has benefits ahead of water based systems in that properties of CO₂ (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. For similar reasons, there is growing interest in the use of supercritical (sc) CO₂ in closed loop power cycles as a replacement for steam (e.g. in fossil fuel-fired or nuclear power plants).  
  - **Enhanced production** – production of urea using CO₂ captured from H₂ production – an integral step in the Haber-Bosch process used to make ammonia, a precursor for urea – is standard practice in fertiliser production. The stoichiometry of ammonia/urea production means that typically, where natural gas is used to make H₂, there is not enough captive CO₂ to convert all the ammonia to urea. Using non-captive sources of CO₂ can be used to boost urea production from surplus ammonia, and is increasingly being practised in industry. Similarly, methanol production can be enhanced by adding CO₂ to the syngas used to produce methanol. |
| Enhanced hydrocarbon recovery | Use of CO₂ in energy production can be carried out through several process, including:  
  - **Miscible/immiscible floods** – flooding hydrocarbon reservoirs with injected CO₂ can improve recovery factors (RF) from fields, by either miscible processes (where the CO₂ dissolves with oil, reducing its viscosity and therefore enhancing its flow to production wells), or through displacement (immiscible floods). Whilst CO₂-EOR is proven, the potential for CO₂-EGR is uncertain because gas fields typically already have high RFs under conventional depletion (>70%). |
- **Sorption-based displacement** – enhanced coal bed methane (ECBM) production involves injection of CO₂ into deep, unmineable coal seams (unmineable is largely an economic term) where it is preferentially absorbed to the coal and the methane desorbed. The displaced methane is collected at the surface via wells for use as a substitute for natural gas. Nitrogen may also be used for ECBM, where it reduces the partial pressure of methane on the coal seams. This suggests the possibility for direct injection of flue gases (without the need to strip out the CO₂ fraction).

### CO₂ mineralisation

Transformation minerals containing calcium and magnesium (usually bound as silicates) through the addition of CO₂ leads to the formation of carbonates. This basic chemical process has a number of potential applications, including:

- **Carbonate mineralisation (building products etc)** – mineral carbonation occurs naturally and is a very slow process. It may be accelerated using heat, pressure, chemical processing or mechanical treatment (grinding) and the addition of CO₂ to produce a range of materials including building aggregates and cementitious products.
- **CO₂ concrete curing** – concrete curing is a process employed after it is placed to improve its strength and hardness. Over time, curing continues through adsorption of CO₂ from the atmosphere, with the conversion of calcium hydroxide present in cement to calcium carbonate. Various technologies involving CO₂ are under consideration to improve and accelerate concrete curing processes.
- **Bauxite residue carbonation (red mud)** – The extraction of alumina from bauxite ore results in a highly alkaline residue slurry (known as ‘red mud’). A new technology has been developed whereby concentrated CO₂ 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 CO₂ and reducing the pH of the slurry to a less hazardous level.

### Chemicals production

Use of captive or non-captive CO₂ for synthesis of chemicals is standard practice for some chemicals, although for many new applications are emerging that offers potential to use CO₂ based processes as a substitute for other production methods. These include:

- **Sodium carbonate** – 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 CO₂ to ammoniated brine which leads to the precipitation of sodium bicarbonate, which is processed to form soda ash. CO₂ is also required in other parts of the process. New methods are under consideration for using CO₂ for sodium bicarbonate production.
- **Polymers** - polymer processing (feedstock for polycarbonates) – production of polycarbonates and polyurethane using phosgene gas can be replaced by safer methods using CO₂ to produce carbamate precursors as a source for C1 carbon in production.
- **Other chemical synthesis (e.g. acetic acid)** – as well as precursors for polymer production, a wide array of other potential applications for CO₂ 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; acetone fermentation; aliphatic aldehydes from alkanes etc. Research into innovative chemical conversion processes, in particular the mimicking of natural photosynthesis, which involves conversion of CO₂ through photo-chemical, electro-chemical and biochemical reactions to produce high energy carbohydrates (as in plants) is also underway. Photocatalysis is also considered promising as a means to extend artificial photosynthesis beyond carbohydrate production into other chemicals. Electrochemical reduction of CO₂ using renewable energy could also provide new pathways for production of methane, methanol and formic acid (see ‘CO₂ to fuels’ above).
- **Algae (for chemicals)** – as for production as for ‘CO₂ to fuels’ above. Algal oil has potential in many of the world’s largest markets including livestock feed, agricultural fertiliser, oleochemicals, as well as pharmaceutical and nutraceuticals markets. Additional processing options also offer potential for production of a high value char product, suitable in many instances as a metallurgical char, activated carbon or for soil remediation and bio-sequestration.
4.2 What is their current status?

As mentioned previously, the different technologies outlined in Table 2 are at differing stages of maturity. Some of the incremental technologies could be readily established in existing mature markets e.g. use of CO₂ to boost urea production, whereas others are at the theoretical and research phase, or are at the pilot/demonstration phase, and need further development to reach commercial status. In some circumstances, certain technologies are viable under certain conditions e.g. application of CO₂-EOR, but requires a niche set of circumstances for this to be applied on a large and replicable scale (as exists for CO₂-EOR in parts of the United States of America (US)). In other environments, technical factors could limit such application e.g. CO₂-EOR has never been tested in an offshore environment.

A provisional attempt has been made to classify their status, drawing on previously developed definitions of technical maturity e.g. that used by the Intergovernmental Panel on Climate Change (IPCC; Table 2) (Metz et al., 2005). Within this assessment, no consideration has been given to the maturity of various technologies through which CO₂ might be captured. Where a particular technology holds potential to achieve various policy goals, it will likely be necessary to support their development through policy interventions so that they may progress through the development cycle, as discussed in Part 2 of this report.
Table 2 - Technical maturity of various CCU technologies

<table>
<thead>
<tr>
<th>CCU category</th>
<th>CCU technology</th>
<th>Research</th>
<th>Demonstration</th>
<th>Economically feasible under certain conditions</th>
<th>Mature market</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂ to fuels</td>
<td>Hydrogen (renewable methanol)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Hydrogen (formic acid)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Algae (to biofuels)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Photocatalytic processes</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Nanomaterial catalysts</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Enhanced commodity production</td>
<td>Power cycles (using scCO₂)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Enhanced production (urea; methanol)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Enhanced hydrocarbon recovery</td>
<td>Miscible/immiscible floods (CO₂-EOR)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Miscible/immiscible floods (CO₂-EGR)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Sorption-based displacement (ECBM)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CO₂ mineralisation</td>
<td>Cement production</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>CO₂ concrete curing</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Bauxite residue carbonation (red mud)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Carbonate mineralisation (other)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chemicals production</td>
<td>Sodium carbonate</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Polymers</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Other chemicals (e.g. acetic acid)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Algae (for chemicals)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Legend

Main activities
Some activities

'Research' means that while the basic science is understood, the technology is conceptually feasible and some testing at the laboratory or bench scale has been carried out, it has not yet been demonstrated in a pilot plant. 'Demonstration' means that the technology has been, or is being, built and operated at the scale of a pilot plant, but that further development is required before the technology is ready for use in a commercial/full scale system. 'Economically feasible under certain conditions' means that the technology is well understood and is applied in selected commercial applications, although it has not been proven in all conditions. 'Mature market' means that the technology is in commercial operation with multiple replications, or could be easily modified to accommodate new applications involving non-captive CO₂.

Attempts have been made by others to assess when certain technologies may be market mature, as shown below (Figure 2). The basis for the estimated deployment timescales claimed by technology proponents is unclear, and it is possible that some may be overly optimistic. The figure therefore also indicates a more pragmatic view of the potential timeframe to commercialisation. Pre-commercial

---

* Technology statuses classification based on Metz et al (2005)
CCU technologies face a range of obstacles to commercialisation: these include successful demonstration of the technology/application itself (i.e. overcoming R&D challenges) and also external factors (e.g. competition from alternative services and goods, public acceptance). The current development status of key CCU technologies, and how they can be stimulated and accelerated, will be explored further in Part 2.

![CCU technology development timeline](image)

Figure 2 - CCU technology development timeline (Parsons Brinkerhoff/GCCSI, 2011)

4.3 Who is involved in their development?

The diversity of CCU technologies under review – and the differing technical maturity of the various applications – inevitably means that a wide range of actors are involved in the research and development of CCU technologies. Key stakeholders include:

- **Academia/research** – a number of universities and research organisations are involved in CCU development. The key faculty with interests in CCU tends to be chemical engineering (e.g. University of Sheffield, UK; University of Aachen, Germany; Abo Akademi, Finland), whilst a number of research institutions around the world are developing strands of CCU research (e.g. National Labs, US; Fraunhofer Umsicht Institute; Max Planck Institute and Forschungszentrum Jülich, Germany). These organisations play a key role on the research phase of technology development through conceptual design and laboratory scale
experiments. They are also important in establishing partnerships with industry in order to move from laboratory scale experiments into pilot and demonstration scale projects implemented in an industrial setting. This can help to leverage industry know-how in scaling up technologies.

- **Start-ups/spin-offs/venture capital** – a number of small start-up companies, in some cases either spun-off from Universities or developed through venture capital, are involved in pioneering demonstration scale CCU technology developments. Organisations include Joule Unlimited (US; Helioculture), Calera (US; CO₂ mineralisation), Novacem (UK/Imperial College, CO₂ mineralisation). These actors play a key role in demonstrating research concepts and bringing technologies through to commercialisation.

- **Industry** – large companies are also involved in the development of CCU technologies. Examples include Bayer (Germany), BASF (Germany), Evonik (Germany) and Siemens (Germany). These actors are pivotal in bringing promising demonstration technologies through to commercial application. Many are also involved in more fundamental R&D in association with academic and research institutes;

- **Industry & research groups** – support of industry bodies, such as trade associations, is important for unifying research efforts and lobbying for R&D funding and other forms of policy support such as effective regulatory, fiscal and incentives design. Organisations such as DECHEMA (Germany) and CO₂CHEM (UK) are effective in bringing together various actors involved in CCU development to build collaborative efforts and create unified voice on a number of issues. Collaboration amongst industry and academia in such fora is important part of driving innovation from research to demonstration and deployment;

- **Policy-makers** – are responsible for developing appropriate frameworks to support technologies which can help to achieve policy aims. In some countries research in to CCU technologies is stimulated by national subsidy programmes. In the US, the Department of Energy is investing in several dedicated research programmes. In Europe, the European Commission is stimulating R&D through EU Framework Programmes and also Member State governments, such as the German government, are investing in the development of CCU technologies through a wide number of research budgets. The German Federal Ministry of Education and Research (BMBF) implemented a subsidy programme to stimulate CCU technologies, with a particular focus on chemical applications.

A summary of some of the actors involved in the various CCU technology categories is shown below (Table 3).
Table 3 - Actors involved with CCU (selected)

<table>
<thead>
<tr>
<th>CO₂ to fuels</th>
<th>Academia</th>
<th>Start ups</th>
<th>Industry</th>
<th>Others</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max Planck Inst (DE)</td>
<td>Granit Green (CH)</td>
<td>DNV-KEMA (NO)</td>
<td>Bayer (DE)</td>
<td></td>
</tr>
<tr>
<td>Swiss Fed Inst Tech</td>
<td>Blue Petroleum (ES)</td>
<td>Mantra Energy Venture (CA)</td>
<td>RWE (DE)</td>
<td></td>
</tr>
<tr>
<td>Bielefeld Uni (DE)</td>
<td>Microphyt (FR)</td>
<td>Siemens (DE)</td>
<td>Abengoa (ES)</td>
<td></td>
</tr>
<tr>
<td>Wageningen Uni (NL)</td>
<td>SAT (A)</td>
<td>Holcim (CH)</td>
<td>IOC (e.g. Shell)</td>
<td></td>
</tr>
<tr>
<td>Uppsala Uni (SE)</td>
<td>Subitec (DE)</td>
<td>IOC (e.g. Shell)</td>
<td>ABNT (ES)</td>
<td></td>
</tr>
<tr>
<td>VITO (B)</td>
<td>Liquid Light Inc (US)</td>
<td>Carbon Recycling International (IS)</td>
<td>QAFAC (QA)</td>
<td></td>
</tr>
<tr>
<td>Fraunhofer Umsicht Institute (DE)</td>
<td>Sapphire Energy (US)</td>
<td>Olis (IS)</td>
<td>Saudi Methanol (KSA)</td>
<td></td>
</tr>
<tr>
<td>Ben Gurion Uni (IL)</td>
<td>Aurora Biofuels (US)</td>
<td>Century Aluminium (IS)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sandia Natl Lab (US)</td>
<td>Live Fuels (US)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Uni Calif (San Diego)</td>
<td>Solix Biofuels (US)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Penn State Uni (US)</td>
<td>GreenFuel Tech (US)*</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mitsu Chem (JP)</td>
<td>Parabel (US)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jinan University (CN)</td>
<td>Algae Bio-Tech India</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Quaid-i-Azam Uni (PAK)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Qatar Diar Construct ENN Group (CN)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Enhanced commodity production</th>
<th>Academia</th>
<th>Start ups</th>
<th>Industry</th>
<th>Others</th>
</tr>
</thead>
<tbody>
<tr>
<td>CEA (FR)</td>
<td>GreenFire Energy (US)</td>
<td>MHI (JP)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Uni of Minnesota (US)</td>
<td>Geodynamics (AUS)</td>
<td>QAFAC (QA)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sandia Natl Lab (US)</td>
<td>Origin Energy (AUS)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NREL (US)</td>
<td>Heat Mining Co (US)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LLNL (US)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Enhanced hydrocarbon recovery</th>
<th>Academia</th>
<th>Start ups</th>
<th>Industry</th>
<th>Others</th>
</tr>
</thead>
<tbody>
<tr>
<td>Indiana Uni (US)</td>
<td>2CO (UK)</td>
<td>Gdf (FR)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LBNL (US)</td>
<td></td>
<td>Vattenfall (SV)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Uni Western Australia</td>
<td></td>
<td>Occidental (US)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Anadarko (US)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Denbury Resources (US)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Kinder Morgan (US)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>CO₂ mineralisation</th>
<th>Academia</th>
<th>Start ups</th>
<th>Industry</th>
<th>Others</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sheffield Uni (UK)</td>
<td>Calera (US)</td>
<td>Bayer (DE), RWE (DE)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aachen Uni (DE)</td>
<td></td>
<td>BASF (DE), Siemens (DE), Evonik (DE)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Newcastle Uni (UK)</td>
<td></td>
<td>Shell (UK/NL)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Abo Akademi (FI)</td>
<td></td>
<td>RWTH Aachen</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MacGill Uni. (US)</td>
<td></td>
<td>SINTEF (NO)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rutgers Uni. (US)</td>
<td></td>
<td>Eastman Kodak (US)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A*Star (SG)</td>
<td></td>
<td>Praxair (US)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>CNOCOC (CN)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Feyecon (NL)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Chemicals production</th>
<th>Academia</th>
<th>Start ups</th>
<th>Industry</th>
<th>Others</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uni. of Aachen (DE)</td>
<td>Coates Group (US)</td>
<td>Bayer (DE), RWE (DE)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Uni. Newcastle (UK)</td>
<td></td>
<td>BASF (DE), Siemens (DE), Evonik (DE)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Uni. of Sheffield (UK)</td>
<td></td>
<td>Shell (UK/NL)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Uni. of Twente (NL)</td>
<td></td>
<td>RWTH Aachen</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MIT (US)</td>
<td></td>
<td>SINTEF (NO)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TNO (NL)</td>
<td></td>
<td>Eastman Kodak (US)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Praxair (US)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>CNOCOC (CN)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Feyecon (NL)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* GreenFuel Technologies shut down its algae biofuel production plant in 2009 due to lack of financing.
As well as individual organisations, trade groups and associations of academics, the evolution of new and complex value chains required to support more novel types of CCU technologies will mean that broad collaboration between various commercial actors will be necessary. New forms of partnership between various companies and sectors – especially where there have been no traditional commercial relationships – will need to be built, such as between the power sector (as CO₂ suppliers) and the chemical sector (as CO₂ users). For some technologies, these types of relationships are starting to emerge through joint demonstration projects, for example the Bayer-led DREAM project and collaborations between BASF and Siemens (Box 1).

**Box 1 - Polymer production demonstrates successful collaboration (Bayer, 2012)**

The DREAM production project is a collaborative research and demonstration project led by BAYER MaterialScience (a division of Bayer Group). The project involves taking CO₂ captured from the flue of a lignite-fired power plant owned and operated by RWE at Niederaußen and its transport to Bayer’s Leverkusen Plant in Germany where it is used on the production of polycarbonate polyol ("PPP"), a key building block in the manufacture of lightweight polyurethane foam material. The final product is ultimately destined for use in applications such as the manufacture of furniture (e.g. mattresses), automotive parts and as an insulator in buildings and refrigerators. The use of CO₂ will partially substitute the use of petrochemical products traditionally used in making PPP. The key to the success of the technology was the development of an appropriate catalyst to activate CO₂ and allow it to split.

The project involves a number of partners including:

- Bayer Technology Services (plant design and construction)
- RWE (supply of CO₂)
- WTH Aachen University
- CAT Catalytic Centre (Aachen University)

Bayer has been running batches in the pilot plant for several years and plans to move the system into commercial production by 2015. Bayer is also planning other activities involving CO₂ – one idea is to find and efficient method to convert the CO₂ into carbon monoxide, a key basic chemical that could in turn be used to produce another component for polyurethanes. This, it claims, would close the carbon cycle in the polymer production. The DREAM project received UNEP's "365 Landmarks in the Land of Ideas" award in 2012.

The Dream Production project is funded by Bayer MaterialScience with €6.05m and by Bayer Technology Services with €1.25m. RWTH Aachen University and the State of North Rhine-Westphalia contributed €2.7m for the programme. The government is contributing about €5m for the Dream Production.

**BASF, Evonik and Siemens are also pursuing similar lines of research in Germany.**

### 4.4 Are there any environmental, health or safety issues associated with their development?

On the whole, the CCU technologies reviewed in this report are reportedly environmentally benign, although in many cases further research is needed to clarify the relative impacts compared to more
conventional process pathways. The capture of CO\textsubscript{2} from industrial and energy related sources will pose the same sorts of environmental, health and safety (EHS) concerns as highlighted for CCS (e.g. handling of large amounts of chemicals such as amines; issues associated with handling high pressure CO\textsubscript{2}). Likewise, technologies which result in the geological storage of CO\textsubscript{2} (e.g. CO\textsubscript{2}-EOR or EGS\textsubscript{CO}\textsubscript{2}) will also pose similar risks as that of geological storage of CO\textsubscript{2} (e.g. risk of CO\textsubscript{2} leaks from the subsurface, impermanence of emissions abatement). These issues have been discussed in various papers (European Commission, 2008a), and will not be reviewed again here.\textsuperscript{5}

In terms of broader EHS issues, some CCU technologies do offer environmental advantages:

- **Bauxite carbonation** (*"red mud") – as set out in Table 1 this emerging technology is being developed to stabilise alkaline mine tailings, with attendant environmental benefits;
- **Polymers** – the use of CO\textsubscript{2} to manufacture polycarbonates is potentially an important breakthrough for environmental and occupational health and safety reasons. The conventional method for polycarbonate production involves the reaction of bisphenol A with phosgene gas. Both constituent parts present EHS concerns: bisphenol A is a known endocrine disrupting substance, which has raised public health concerns over the exposure of humans to trace levels in polycarbonates used in food containers and other consumer products (e.g. compact discs). Also, phosgene is a highly toxic gas, posing occupational health issues during the production of polycarbonate. Alternative production pathways using CO\textsubscript{2} can help to eliminate the need for at least some of these chemicals in the production process. For example, the use diphenyl carbonate as a replacement for phosgene gas in the synthesis of polycarbonate is under consideration by a number of companies (e.g. Novomer, Bayer, BASF). Various other alternative pathways for polycarbonate and polyurethane production are also under consideration, which could eliminate the most toxic chemicals used in production (although further research on the relative toxicity of various production pathways is needed to clarify the relative impacts).
- **Algae and photocatalytic routes to biofuels** – one of the benefits of algae-based production system is that they can take place on marginal land using brackish water. This essentially eliminates land competition for other uses, such as agricultural production, and also for potable water resources, which are major drawbacks of more traditional biomass-based fuels (e.g. corn, soya).

In terms of negative impacts, potentially significant environmental issues are presented by applications involving **CO\textsubscript{2} mineralisation processes**. These will require large amounts of mining of the various magnesium and calcium-bearing silicate minerals that are required for the transformation process (Table 1). The cost and potential environmental damage of these activities poses one of the greatest challenges for large-scale uptake of this technology (Table 4). On the other hand, these minerals may be available in abundance in mine tailings, and therefore could present an option for using otherwise waste resources generated as a by-product of mining.

\textsuperscript{5} For example, see: COM (2008a)
Table 4 - Silicate requirements for CO₂ mineralisation

<table>
<thead>
<tr>
<th>Mineral</th>
<th>Tonnes per ton CO₂</th>
<th>Estimated mining requirements</th>
<th>Product (tonnes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Olivine</td>
<td>1.6</td>
<td>6 – 8 times the size of coal mining operation (for mineralisation from coal-fired power plant)</td>
<td>2.6</td>
</tr>
<tr>
<td>Serpentine</td>
<td>2.3 – 3.6</td>
<td></td>
<td>3.3 – 4.7</td>
</tr>
<tr>
<td>Wollastonite</td>
<td>2.6</td>
<td></td>
<td>3.6</td>
</tr>
</tbody>
</table>

Source: adapted from LCF (2011); It has been suggested that the different nature of deposits of olivine (usually surface and in thick seams) compared to coal seams means that the overall impact of mineral mining may be less (Lackner et al., 1995; Ziöck et al., 2000)

For most of the remaining technologies, direct impacts have not been closely evaluated, or are relatively minor. For example, it has been reported that emissions from methanol cars are low in reactive hydrocarbons (which form smog) and toxic compounds in comparison to fossil fuel-based road transport fuels; algae based systems could potentially be applied in conjunction with wastewater treatment, lowering overall costs and impacts of algae cultivation.
5 What are the economic factors involved in CO₂ reuse?

As outlined previously, CO₂ is currently used in a wide range of commercial applications, from food and beverage production to horticulture, electronics, pharmaceuticals and steel manufacture. However, the market for these existing uses of CO₂ is limited – for most industries, the annual global demand for CO₂ amounts to a few million tonnes or less. Furthermore, with very few exceptions, these existing uses do not necessarily result in emissions abatement, either through the storage of CO₂ or through the substitution of more carbon-intensive products and services. Although the potential for CCU from existing applications is expected to increase (for example, with growing worldwide demand for food and beverage processing), a step-change in the uptake of CCU – and therefore its ability to meet various climate, energy and industrial policy objectives – will require the development of new uses for CO₂.

These new, or emerging, applications (described in Section 3 above) are currently at very different stages of commercialisation. Although certain applications, such as CO₂-EOR and urea yield boosting have been proven to be commercial in certain settings and regions worldwide, most other CCU technologies remain at the early stages of commercialisation (Table 2). The uptake of these technologies and their potential to be scaled-up from the lab-test and pilot level to commercial scale will depend on various economic factors. Although policy plays an important role in creating the enabling frameworks to support technology and market development – particularly in the early stages – the levels of investment and innovation required for widespread CCU will need the active participation of the private sector.

Investing in new plant and processes will require industry to develop sound business cases with acceptable pay-backs and commercial risk levels and for policy-makers to develop effective policy and market interventions. Both require an understanding of the factors underpinning the potential commercialisation of CCU applications. Key economic factors driving the development of CCU technologies within the EU and elsewhere include:

- **The potential to generate value from products and services which utilise CO₂** (creating revenues and/or avoiding costs)
- **Market demand and outlook** (potential CO₂ volumes that could be used)
- **Costs** (capital, energy and other cost components, and the potential for their reduction)
- **Barriers to commercialisation** (market, cost, and other factors)

---

6 This refers to ‘non-captive’ sources of CO₂ only, namely CO₂ which needs to be sourced externally to the process. The distinction between ‘non-captive’ and ‘captive’ CO₂ is important as statistics for urea manufacture show a global requirement for over 100 MtCO₂/yr. However, this CO₂ is produced from the fossil fuel feedstock to the urea production process, and therefore CO₂ does not need to be sourced externally (Parsons Brinckerhoff/GCCSI, 2011).
Due to the embryonic nature of many of the technologies under consideration, it has not been possible to make a comprehensive and quantitative analysis of the cost factors involved with different technologies, although the following sections discusses these factors further.

5.1 Creating value from products and services

CCU offers the potential to use a waste stream (CO₂-emissions) in the production of commercial products and services. The creation of value-added commodities such as fuels, fine and bulk chemicals and building materials using CO₂ can provide the revenues needed to offset upfront investments and ongoing production costs. CO₂ can also be used to improve industrial production efficiency, or to produce additional services, thereby reducing production costs and/or increasing revenues e.g. through the potential application of supercritical CO₂ as a working fluid in power generation and geothermal energy extraction.

Conversely, emitting CO₂ poses a significant cost to industry – in Europe, most emissions from industry fall within the scope of the EU Emissions Trading Scheme (ETS), and other carbon trading and tax regimes are emerging worldwide. Where the utilised CO₂ is either permanently stored (e.g. through mineralisation and, potentially, through CO₂-EOR) or leads to net emissions reductions (e.g. through the substitution of fossil- with renewable-based liquid fuels), or even temporarily stored (e.g. through fuel production), then there is potential for these carbon costs to be avoided. In certain cases, CCU could also generate revenues through emissions reductions undertaken under the Clean Development Mechanism (CDM) or other project-based mechanisms. The exact potential for these benefits to be realised will depend on the specific rules regarding technology eligibility, boundaries for reporting, and permanence within specific schemes.

Importantly, costs arising from carbon schemes impact both producers and end-users of products and services, thereby creating a demand and ‘price signal’ for emission reductions across the value chain from supply to consumption. In some cases, the exact value and potential implementation costs could be affected by the rules applied in the scheme in relation to e.g. reporting boundaries and monitoring, reporting and verification; MRV – see Section 3.3 of Part 2.

CO₂ utilisation can therefore potentially create value through the generation of revenues and/or the reduction of production costs. However, at present many CCU technologies are yet to be proven commercially, having high capital costs, large energy requirements and associated financial risks to increased investment. Similarly, as with CCS, CO₂ prices within the EU ETS and elsewhere are currently too low to provide long-term support for CCU beyond the demonstration phase. However, as the costs of CCU are expected to fall with ongoing R&D efforts, innovation and policy support, the factors determining revenues are also not fixed in time. An important consideration here is the potential for CCU technologies to compete with, and substitute, existing products and services. While patterns and levels of demand for commodities such as liquid fuels, electricity and chemical products change over time, so to do the factors influencing the specific process routes by which they are produced. These factors can be both economic and non-economic on nature. For example, despite
the currently prohibitively high costs, much of the current CCU R&D activity in the EU and elsewhere is focused on the production of renewable liquid fuels (predominantly for use in transportation) and also on chemicals production. In most cases, these will need to compete with conventional fossil-fuel products such as diesel, petroleum and kerosene. However, as global oil production potentially declines over coming years (reaching so-called "peak oil"), increasing fuel prices combined with policies aimed at enhancing energy security and reducing transport emissions can be expected to increasingly favour the use of alternative fuels. Rising fossil fuel prices and concerns over increasing imports are also important economic drivers for the increased use of CO₂ in enhanced hydrocarbon recovery. ⁷ Such developments have the potential to increase revenues, both in terms of unit sales (e.g. € per tonne product) and also absolute volumes (e.g. market share).

The factors influencing how value can be created from CCU are complex and will necessarily be subject to many uncertainties. The successful commercialisation of CCU technologies will therefore likely require the use of systematic, or ‘joined up’ approaches to maximising the value of CO₂ pathways in which revenues can be maximised - and costs and risks reduced. One example described in a recent study by Low Carbon Futures (2011) is the combination of CCS with CCU to help recover investment costs and optimise project economics. In the case described, CO₂ captured from a coal-fired power plant might either be geologically stored or used to produce synfuels. This flexibility would in theory allow operators to select the optimal CO₂ pathway according to external market dynamics i.e. the carbon price under the EU ETS versus the synfuel price (see Section 6.2). Similarly, some CCU technologies offer pathways to the creation of multiple commercial products. For example, algae cultivation can result in the production of not only renewable fuels, but also chemicals, pharmaceuticals, nutraceuticals, food and stock feed. This offers the potential for CCU technologies to enter more than one market, thereby offering some degree of commercial flexibility and risk reduction (e.g. arising from exposure to demand or price volatility). Further, algae-to-biofuel routes face challenging market entry barriers as they attempting to substitute a high volume/low value product, namely petroleum/diesel. On the other hand, if both petroleum substitutes and other co-products such as nutraceuticals can be made from algae, market entry barriers will be lower for these low volume/high value goods, meaning vital revenue streams could be made available to reduce the net cost of biofuel production (POST, 2011).

The scope for ‘joined up’ approaches to the development of CCU technologies, and the various pathways and products associated with CCU has the ability to bring important co-benefits across various strands of EU policy (e.g. climate action, energy, industrial policy and innovation). In this way, CCU also has an important and potentially reinforcing role to play across all three of the thematic priorities contained in the Framework Programme for Research and Innovation (Horizon 2020) (European Commission, 2011a), namely:

1. **Excellent Science** – aims to raise the level of excellence in Europe's science base; a key component is to fund collaborative research to open up new and promising fields of research and innovation through support for “future and emerging technologies” (FET).

---

⁷ The commercial operation of CO₂-EOR operations in North America (e.g. Weyburn and Rangely) is partly achieved through a governmental fiscal incentive framework which recognises the benefit of enhancing domestic oil and gas production.
2. **Industrial Leadership** – aims to make Europe a more attractive location to invest in research and innovation (including eco-innovation); aims to *build leadership in enabling and industrial technologies, with dedicated support for ICT, nanotechnologies, advanced materials, biotechnology, advanced manufacturing and processing*’

3. **Societal Challenges** – funded activities will address challenges including ‘secure, clean and efficient energy’, ‘smart, green and integrated transport’ and ‘climate action, resource efficiency and raw materials’

### 5.2 What is the market demand for CCU?

Table 5 summarises current estimates of the future potential for CO₂ utilisation across various CCU applications.\(^8\)

The ranges shown indicate that there is thought to be significant potential for CCU across a wide range of applications, most noticeably involving the production of fuels using CO₂ and mineralisation (up to several GtCO₂ per year in total). These findings are broadly consistent with other studies which estimate for example the potential for CCU at 10% for the fuels sector and between 1-7% for the chemicals sector and (Aresta, 2010; VCI & DECHEMA in Germany, 2009). \(^9\) Some estimates consider the technical potential for some applications to be an order of magnitude higher again. For example, a recent study has estimated the worldwide potential capacity for carbonate mineralisation alone at 5 GtCO₂ (Zevenhoven, 2009), although such figures should be treated as purely theoretical only.

---

\(^8\) The applications shown cover ‘non-captive’ sources of CO₂ only, and do not include the extensive list of existing commercial uses for CO₂ where both existing and forecast demand is typically a few million tonnes per year or less.

\(^9\) However, this is based on a limited number of chemical reactions to give a limited number of products. As R&D progresses in new areas of catalysis and C-1 chemistry to build more complex molecules, then it should become apparent that the market is less limited (Low Carbon Futures, 2011)
### Table 5 - Estimated global long-term demand for CCU applications

<table>
<thead>
<tr>
<th>CO₂ reuse category</th>
<th>Technology or application</th>
<th>Long-term demand potential</th>
<th>Potential for GHG emissions reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>MtCO₂ used per year</td>
<td>CO₂ storage potential</td>
</tr>
<tr>
<td>CO₂ to fuels</td>
<td>Algae cultivation</td>
<td>&gt;300</td>
<td>Not permanent where used in fuel production</td>
</tr>
<tr>
<td></td>
<td>Renewable methanol</td>
<td>&gt;300</td>
<td>CO₂ released upon fuel combustion</td>
</tr>
<tr>
<td></td>
<td>Formic acid</td>
<td>&gt;300</td>
<td>CO₂ released upon fuel combustion</td>
</tr>
<tr>
<td></td>
<td>Hydrocarbon excreting micro-organisms</td>
<td>&gt;300</td>
<td>CO₂ released upon fuel combustion</td>
</tr>
<tr>
<td>Enhanced commodity production</td>
<td>Urea yield boosting</td>
<td>5 – 30</td>
<td>6 months</td>
</tr>
<tr>
<td></td>
<td>Methanol yield boosting</td>
<td>1 – 5</td>
<td>6 months</td>
</tr>
<tr>
<td></td>
<td>Enhanced geothermal systems with CO₂</td>
<td>5 – 30</td>
<td>Permanent storage via CCS may be feasible</td>
</tr>
<tr>
<td></td>
<td>Supercritical CO₂ power cycles</td>
<td>&lt;1</td>
<td>Not thought to be feasible</td>
</tr>
<tr>
<td>Enhanced hydrocarbon production</td>
<td>Enhanced oil recovery (EOR)</td>
<td>30 – 300</td>
<td>Permanent when combined with CCS</td>
</tr>
<tr>
<td></td>
<td>Enhanced coal bed methane (ECBM)</td>
<td>30 – 300</td>
<td>Permanent when combined with CCS</td>
</tr>
<tr>
<td>CO₂ mineralisation</td>
<td>Carbonate mineralisation</td>
<td>&gt;300</td>
<td>Decades to centuries</td>
</tr>
<tr>
<td></td>
<td>CO₂ concrete curing</td>
<td>30 – 300</td>
<td>Decades to centuries</td>
</tr>
<tr>
<td></td>
<td>Bauxite residue treatment</td>
<td>5 – 30</td>
<td>Decades to centuries</td>
</tr>
<tr>
<td>Chemicals production</td>
<td>Polymer processing</td>
<td>5 – 30</td>
<td>Decades to centuries</td>
</tr>
<tr>
<td></td>
<td>Sodium carbonate</td>
<td>&lt;1</td>
<td>Semi-permanent</td>
</tr>
<tr>
<td></td>
<td>Other (non-fuel) chemical synthesis</td>
<td>1 – 5</td>
<td>Varies according to process</td>
</tr>
</tbody>
</table>

Note: does not consider life-cycle assessment of GHG emissions, which are highly variable and case-specific. The term 'permanent' here refers to CO₂ removed from the atmosphere and stored over a long period e.g. 1,000 years.

Sources: Adapted from Parsons Brinckerhof/GCCSI (2011) and IPCC (2005)

The estimates of future demand shown in the table and from other sources indicate a large degree of uncertainty around the potential CO₂ volumes which may be utilised through CCU. These reflect a large number factors associated with both the supply of CCU-derived commodities and services and the demand for CCU. This interaction of supply and demand factors will shape the way in which the market for CCU technologies develops over time. These considerations can be highly specific to different applications and sectors and are summarised for each CCU option in Table 6. Other, more generic factors are likely to include:
• **Overall market size** for products and services which can be provided through CCU – which will be driven by various macroeconomic and geographical factors;

• **Market competition from other products and processes**, including low-carbon alternatives e.g. hybrid and electric vehicles; other green building products;

• **Evolution of regulatory, policy and technical framework** e.g. building codes and product standards, fuel quality specifications, vehicle/equipment/plant guarantees;

• **Consumer preference for products and services**, including public acceptability/support for CCU applications compared with alternatives – key factors are likely to include successful demonstration of the environmental and/or economic benefits of CCU;

• **Ability to identify the potential for introducing new processes and pathways** for CCU in supply chains, through the effective interaction of producers and consumers;

• **Successful demonstration of CCU technologies** at scale and across different settings;

• **Ongoing reduction in capital and production costs** for CCU (see section below).

Table 5 also summarises the factors influencing the emissions abatement potential for each CCU application, including the potential for the application to result in permanent storage of CO₂ or result in abatement through other effects e.g. fuel substation or improved process efficiency. It can be seen that these factors are highly variable across the applications, and that also, for some options, there are no clear indications that CO₂ utilisation results in any net emissions reduction benefit. ¹⁰ This is particularly noticeable in the case of CO₂ to fuels, in which the combination of CO₂ reuse with permanent storage is typically not feasible; in these cases, emissions benefits typically rely on the potential to substitute hydrocarbon based fuels.

It is important to note therefore that realising the significant demand potential for CCU is not necessarily consistent with achieving a proportional reduction in global GHG emissions. A recent paper (DNV, 2011) has estimated, however, that a combination of CCU technologies could potentially reduce annual emissions by 3.7 GtCO₂, which is roughly equivalent to almost 10% of current annual emissions globally. A 10% replacement of building materials by CO₂ captured in stable minerals would reduce CO₂ emissions by 1.6 GtCO₂ per year, and the incorporation of CO₂ into polymers could also account for a 0.4 GtCO₂ reduction (Low Carbon Futures, 2011). The successful development of the market for CCU applications can therefore play a significant role in furthering emissions reduction objectives - as well as other important policy goals.

### 5.3 What are the costs of CCU technologies?

An overriding factor determining the commercialisation of CCU is the cost involved in producing commodities or delivering services utilising CO₂. More specifically, their deployment will be largely determined by the extent to which co

¹⁰ Note also that overlying these factors, are the highly variable considerations relating to the life-cycle production of GHG emissions (e.g. tCO₂e emitted in utilising 1tCO₂)
sts can fall over time compared to competing applications. If their costs cannot be reduced to comparable levels, then CCU technologies will clearly need to demonstrate additional benefits which can create added value or e.g. avoided costs of CO₂ emissions, or be otherwise supported e.g. through policy incentives.

Most CCU technologies are moving from R&D or pilot-scale stage towards demonstration projects (Table 2), and are characterised by high capital and operating costs. A comparative assessment of costs for different CCU applications is difficult: detailed cost studies are not available for all technologies and CO₂ utilisation pathways (i.e. permanent, semi-permanent - such information is often treated as commercially confidential by technology developers), and different assumptions made across different studies mean that a fair comparison cannot be made. For example, a study based on energy cost inputs in one region of the world could result in production costs being twice as large were the same technology deployed elsewhere. However, it can be seen from the summary in Table 6 that costs vary considerably between different CCU applications - both in their overall cost levels (€/tCO₂ utilised, captured or stored) and the specific cost factors comprising them.

Important cost factors for CCU technologies include:

- **Up-front capital costs** – These are typically high for many CCU technologies and may include significant investments in capture plant and industrial production facilities;

- **Energy costs** – Many technologies currently at the R&D stage have prohibitive energy requirements e.g. for undertaking photo-catalysis, algal cultivation or synthetic fuel production. As well as improving the efficiency of these key processes, an important cost factor here is the ability to use surplus or off-peak renewable energy;

- **Operating costs** – Other important production costs include materials and chemicals (e.g. capture solvents, catalysts), increased O&M, labour and land costs.

Whereas some CCU applications are already being deployed on a commercial basis, others will require a major step-change in cost reductions to compete with existing products. For example, it is likely that the costs associated with algae cultivation will need to fall by factor of between 5 and 10 before it can be cost-effective. The large number of R&D programmes currently developing different technology pathways (e.g. open pond systems, photo-bioreactors, hybrid systems) offer the potential for costs to be substantially reduced over the coming decade as process efficiencies are achieved. As demonstrated in numerous cases, from the development of solar photovoltaic (PV) cells to flue gas desulphurisation (FGD) units, step-change technology cost reductions are achieved with the scaling-up of production and dissemination. This is also true of scaling up project sizes, in which scale economy effects can be considerable. The successful demonstration of R&D and pilot-scale CCU technologies in early stages of technology development is therefore essential to scaling-up project sizes and reducing costs.

Many CCU technologies currently face high costs which will need to be overcome through ongoing innovation and process development. It is noticeable that cost estimates are typically highest for those options which may offer step-changes in the use of energy and products from waste CO₂, and also the greatest potential for emissions reduction (e.g. through the production of liquid fuels and the
permanent storage of CO₂ in building products and new chemical products). The need to achieve cost reductions is therefore critical to their success. If the various input costs for CCU applications cannot be reduced to a point comparable with existing, or emerging, alternatives then other drivers (e.g. support through emissions reduction policies) will clearly be required for them to move beyond the pre-commercial stage and attract investment from business and industry.

5.4 Overcoming barriers to commercialisation

As summarised in Table 6, CCU technologies face a wide ranging set of barriers and obstacles to their wider use and commercialisation. Overcoming these presents a complex challenge and will likely depend on various factors lying outside the direct control of individuals, companies and policy-makers. For example, factors driving the development of alternative transport fuels and enhanced hydrocarbon recovery using CO₂ will include those relating to ongoing changes in international energy markets - such as oil and gas price rises, supply and price volatility, new field discoveries, opening up of new frontier exploration provinces (e.g. the Arctic) and the emergence of new technologies for enhancing recovery factors from existing operations (e.g. CO₂-EOR). Other important factors effecting commercialisation can be addressed through policy interventions supporting R&D efforts, to reduce costs and optimising efficiency, and creating enabling frameworks to incentivise emissions abatement, enhance energy security and encourage innovation and green jobs creation.

Many CCU technologies share the same barriers as those faced by CCS. These involve high investment and ongoing project costs, unproven technology at scale and across the full value chain, additional energy requirements (the ‘energy penalty’ associated with CO₂ capture). In the case of CCU resulting in permanent storage of CO₂, ongoing liability, public acceptability and MRV-related issues also need to be considered. However, as seen above, CCU applications typically differ from pure CCS projects in that they create value-added products and services - and these revenues can in turn help to offset project costs. This is evident for example in the case of CO₂-EOR combined with CCS in which the revenues resulting from oil sales may help to offset the high costs of CCS, thereby offering potential early opportunities for CCS.

Similarly, because CCU deployment - unlike pure CCS - is based upon the creation of products and services, it faces a range of barriers specific to the market for those goods, notably its ability to compete commercially within it. As shown in Table 6, these barriers can vary from e.g. existing technologies being technically and economically proven (existing hydrocarbon-based fuels and chemicals; conventional building products) to the need for large-scale infrastructure changes to be made (wide-spread use of CO₂-EOR; formic acid to hydrogen energy). Finally, uncertainty represents a cross-cutting barrier to the development of new technologies and practises, including CCU. Uncertainties concerning technologies, costs, markets, energy prices, revenue streams and emerging policy frameworks pose real risks to business and serve to deter capital investments, particularly at times when gaining access to capital is difficult. Strategies aimed at managing such uncertainties, such as the combination of CCU and CCS described earlier, are therefore likely to play a role in successfully demonstrating CCU at scale, at least in the short-term.
### Table 6 - Summary of key economic and market factors for CO₂ reuse

<table>
<thead>
<tr>
<th>CO₂ reuse category</th>
<th>Technology or application</th>
<th>Sources of revenue</th>
<th>Market development factors</th>
<th>Cost factors</th>
<th>Key barriers to commercialisation</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂ to fuels</td>
<td>Algae cultivation</td>
<td>Large range of potential uses in the development of commercial products, including various biofuels, chemicals and fertilisers</td>
<td>Varies by products and processes; penetration into fuels and chemicals market will be partly determined by economics of competing fossil-fuel products and the evolution of suitable regulatory frameworks.</td>
<td>Cultivation and harvesting costs are currently very high for most technology routes. Depending upon the technology, and algal use assumptions, the costs of large-scale algal oil production has been reported as €4,000-10,000/t, with the potential to fall to €680-1,650/t (representing commercial price levels)</td>
<td>Most algae technologies remain at early R&amp;D stages. The high energy requirements for the mixing of the cultivation system and subsequent biomass de-watering remain a significant obstacle to reducing costs. High land area requirements could also lead to competition from other land uses.</td>
</tr>
<tr>
<td></td>
<td>Renewable methanol</td>
<td>Methanol sales to fuel suppliers (blended with conventional hydrocarbon transport fuels)</td>
<td>Fuel quality specifications likely to limit role of methanol blending; future price of renewable energy and conventional fuels will likely determine uptake outside of Iceland.</td>
<td>Production costs are not available. However, economics are determined by the relative costs of renewable electricity and conventional fuel (which are low and very high, respectively, in Iceland).</td>
<td>Renewable methanol is now at the commercial stage (CRI, Iceland); Competition from alternative transport systems (e.g. electric cars) may limit wide-spread future development.</td>
</tr>
<tr>
<td></td>
<td>Formic acid</td>
<td>Sales of formic acid, and (over longer-term) hydrogen energy carrier</td>
<td>Ability to compete with alternative, emerging, hydrogen energy carriers</td>
<td>Industry claims that formic acid from CO₂ is profitable; cost information for the full chain (to H₂) is not publically available</td>
<td>High capital and energy costs; the key component of formic acid to hydrogen has not yet been successfully demonstrated</td>
</tr>
<tr>
<td></td>
<td>Photo-catalysis</td>
<td>Liquid fuel products</td>
<td>Ability to compete with alternative liquid fuel production routes</td>
<td>Production costs are currently very high. The ability to develop cheap catalysts able to reduce energy needs is key</td>
<td>Cost reductions; improvement in process efficiency and demonstration at scale</td>
</tr>
<tr>
<td></td>
<td>Enhanced commodity production</td>
<td>Urea yield boosting</td>
<td>Production of urea granules and other fertiliser derivatives</td>
<td>Regional demand for urea; market price of urea against ammonia; availability of suitable CO₂ sources</td>
<td>Cost of purchasing CO₂ from nearby source or cost of on-site capture (as low as US$10-20/tCO₂ in some cases)</td>
</tr>
</tbody>
</table>

ECUNL11593 37
<table>
<thead>
<tr>
<th>Enhanced hydrocarbon recovery</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Enhanced oil recovery (EOR)</td>
<td></td>
<td>Increased production of recovered crude oil</td>
<td>Development of ‘mid-stream’ CO₂ infrastructure key to widespread use beyond US and single source-sink projects; evolution of tax incentives; cost of emitting vs. capturing CO₂ (when combined with CCS)</td>
</tr>
<tr>
<td>Enhanced gas recovery (EGR)</td>
<td></td>
<td>Incremental production of natural gas in mature gas fields</td>
<td>Dependent upon gas prices, future demand and relative economics</td>
</tr>
<tr>
<td>Enhanced coal bed methane (ECBM)</td>
<td></td>
<td>Sales of recovered natural gas</td>
<td>Demand for gas is large and forecast to rise; however, ECBM investments will likely need to compete with shale gas in many regions</td>
</tr>
<tr>
<td>CO₂ mineralisation</td>
<td></td>
<td>Construction materials (building aggregates and Portland cement)</td>
<td>Raw materials (Mg and Ca silicates) available in many regions worldwide; substitution of conventional building</td>
</tr>
</tbody>
</table>

Enology Yield Boosting: Increased methanol production (up to 20%) Overall market demand is limited; likely to be driven by methanol prices versus CO₂ capture costs Additional costs arising from capture plant (investment costs, increased energy and other operating costs) Already applied commercially on a limited basis worldwide. Investing in capture plant may be deterred due to methanol price - and demand - volatility.

Enhanced geothermal systems with CO₂: Increased efficiency of electricity generation; avoided cost of CO₂ Significant technical potential worldwide; relative power prices, capture costs and alternative electricity sources all likely to be key Costs arising from capture and transport of concentrated and dehydrated industrial grade CO₂ source Existing water-based EGS processes are under development at a commercial scale; additional CCS-related barriers

Supercritical CO₂ power cycles: Increased efficiency of electricity generation; avoided cost of CO₂ Widespread potential applicability; relative power and CO₂ prices, and capture costs likely to be key factors Costs arising from capture and transport of concentrated and dehydrated industrial grade CO₂ source Little information in the public domain; successful technical demonstration at scale thought to be key barrier

Enhanced hydrocarbon recovery

CO₂ mineralisation
<table>
<thead>
<tr>
<th>Chemicals production</th>
<th>CO₂ concrete curing</th>
<th>Bauxite residue treatment</th>
<th>Polymer processing</th>
<th>Sodium bicarbonate</th>
<th>Other (non-fuel) chemical synthesis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Construction materials; avoided cost of CO₂</td>
<td>Ability to compete with existing conventional building materials</td>
<td>Ability to compete with existing conventional building materials</td>
<td>Ability to compete with existing conventional building materials</td>
<td>Cost information not publicly available</td>
<td>Cost information not publicly available</td>
</tr>
<tr>
<td>Production cost estimated at US$165 per tCO₂ utilised (US DOE, 2010)</td>
<td>Cost information not publicly available; net benefits reported as AU$20 per tCO₂</td>
<td>Cost information not publicly available; net benefits reported as AU$20 per tCO₂</td>
<td>Cost information not publicly available</td>
<td>Cost information not publicly available</td>
<td>Cost information not publicly available</td>
</tr>
<tr>
<td>High production costs and competition from existing market products</td>
<td>Already deployed on a limited commercial basis where factors allow</td>
<td>Entry into large markets such as packaging will require significant cost reductions to compete with existing products</td>
<td>Currently at small-scale demonstration level only; economics largely unknown</td>
<td>High production costs; ability to compete with conventional products/processes; need to demonstrate at scale</td>
<td>High production costs; ability to compete with conventional products/processes; need to demonstrate at scale</td>
</tr>
</tbody>
</table>

- **CO₂ concrete curing**: Materials may require changes to product regulation/specifications. Costs in the range of €60-100/tCO₂ stored (Huijgen, 2007).
- **Bauxite residue treatment**: Avoided costs of bauxite residue storage. High CO₂ purity requirement, limited scale-up potential and applicability constrain deployment potential. Cost information not publicly available; net benefits reported as AU$20 per tCO₂.
- **Polymer processing**: Large range of materials e.g. plastics, coatings, packaging, surfactants. Polymer market is large and growing; ability to compete with existing petroleum-based products is key. Little information is publicly available; cost factors vary considerably by final product and CO₂ pathway. Entry into large markets such as packaging will require significant cost reductions to compete with existing products.
- **Sodium bicarbonate**: Sodium bicarbonate and soda ash. Potential for project scale-up is likely to be limited, given market demand. Cost information not publicly available. Currently at small-scale demonstration level only; economics largely unknown.
- **Other (non-fuel) chemical synthesis**: Range of bulk and fine chemicals e.g. acrylic acid, acetone. Highly variable across markets for chemicals products and processes. Highly variable; existing R&D programmes indicate costs are generally prohibitive at present. High production costs; ability to compete with conventional products/processes; need to demonstrate at scale.
Are there any regional considerations for CCU technology development?
Many CCU technologies may potentially be restricted to niche applications, where appropriate technical and economic conditions exist for their use. Examples of factors affecting the potential for applying CCU technologies include:

- **Availability of high purity CO\(_2\)** – in almost all cases, additional support measures (e.g. carbon pricing) will likely be necessary to reduce the cost of producing CO\(_2\) from anthropogenic sources of a suitable grade for use in most CCU applications. Some suggestions have been made about utilising CO\(_2\) streams without concentration e.g. the direct use if power station flue gases in chemical synthesis. However, research on this potential has been limited to date (North, 2012);
- **Availability/abundance of renewable electricity** – few regions in the world have an abundance of cheap renewable energy resources, which is essential in some CCU applications such as renewable methanol;
- **Availability of suitable silicate minerals** – applications such as bauxite carbonation have been specifically developed to resolve a specific environmental issue. Other mineralisation technologies may be restricted by their proximity to abundant and cheap sources of appropriate silicate chemicals;
- **Availability of land and solar energy** – emerging technologies for algae production or photocatalytic conversions will likely be restricted to low latitude, sparsely populated environments on marginal land with high solar irradiance;
- **Presence of an oil and gas industry** – several of the CCU technologies described are linked to mature hydrocarbon producing provinces;
- **Presence of economic support** – in addition to mechanisms which can support the capture of CO\(_2\), other incentive mechanisms may be required to support certain CCU pathways ahead of, for example, geological storage. In several countries national support programmes are being implemented. In the United States, several reuse technologies are subsidised by the DOE, in Europe in Germany (BMBF – chemical applications) and Spain (Ministry of Science and Innovation - biofuels);
- **Presence of suitable regulatory frameworks** – regulatory frameworks, as described further below, may also be critical to support development of CCU. Examples include recognition of CO\(_2\) stored through CCU as an abatement technology (thus allowing carbon price mechanism to apply to CCU), avoidance of overly complex monitoring regimes, or changes in thresholds non-conventional fuel blend rates (for CO\(_2\) to fuels technologies);
- **Presence of high tech industry** – several of the CCU technologies reviewed relate to high end complex value added products, such as speciality chemicals, and consequently the presence of advanced, high-tech and innovative industrial players can also be seen as a prerequisite for uptake. Supporting networks of research, in particular leading research and technology universities will also be necessary.

As such, many CCU technologies will be restricted to locations where one or more of these factors are in place.
5.5 Europe

Across Europe, several of the factors described above are present in different countries, suggesting that significant potential for CCU technology development exists within the region. It has not been possible to undertake a comprehensive assessment of the technical factors supporting CCU development across the whole of Europe. Suffice to say, several of the factors are present across the whole of the EU-27 (e.g. a carbon price signal), and others are present in several countries. For example, Spain, Italy and Portugal have high levels of solar irradiance and fairly large land areas suitable for algae production and potentially photocatalytic fuel production (Box 2). The UK and Norway both have large and mature oil and gas industries, and other countries in the EU also have smaller hydrocarbon industries that are mature and could be suited to the application of CO₂-EOR and CO₂-EGR (e.g. Austria, Denmark, Germany, Romania).

Box 2 - Algae systems under development across Central and Southern Europe

Although the use of recycled CO₂ for algae cultivation is still in early stages research and development – presently there no closed algal cultivation systems for biomass/biofuel production operating at a commercial scale – there are many emerging pilot or demonstration scale projects within Europe, particularly in Spain, Portugal and Italy. Several major energy companies including BP, Chevron, and Shell have also invested research funding into various systems and are carrying out feasibility studies. Most existing commercial algal systems typically produce high value nutraceuticals. None of the current systems can reliably produce algal biomass year round on a large industrial scale with the necessary yields for meaningful energy production. However, recent activity and investment in the sector is developing rapidly:

- RWE’s pilot project using CO₂ captured from its lignite-powered plant in Niederaußen, Germany was completed at the end of 2011 (ran from 2008-2011); expansion of the project is now envisaged;
- The EC’s FP7 funding programme has funded several demo projects including the BIOFAT demonstration project, the ALL Gas project and the InteSusAl project, although the FP7 call excluded projects involving fossil fuel derived CO₂;
- In 2011, Abengoa Bioenergia (AB) started construction work at the ECOALGA project plant in Cartagena, Spain. The 5000m² experimental plant will be supplied with CO₂ generated by the neighbouring bioethanol facility. The project will evaluate strains of microalgae and cyanobacteria, harvesting techniques, optimum CO₂ concentrations etc, for the production of biofuels and animal feed. The ECOALGA Project has received funding from the Spanish Ministry of Science and Innovation, under the National Plan for Scientific Research, Development and Technological Innovation 2008-2011, and is managed by the Spanish Institute of Oceanography. For the project’s execution, AB receives technical support from the National Centre for Renewable Energies (CENER), the University of Murcia, the Polytechnic University of Cartagena and Ecocarburantes Españoles (Abengoa, 2012);
- BFS Biofuel System SL in Spain has developed an algal based petroleum replacement product (“Blue Petroleum”) and is operating the first continuous cycle industrial pilot plant in Alicante (Spain) since 2010. An Italian shareholder in the company (Enalg S.p.A) holds the exclusive rights in Italy for the production of biofuel from algae using the BFS Biofuel System SL.
- Construction work has started on the Island of Madeira for the first industrial plant to be implemented in collaboration with the local Government and the Electric Power Supply Agency. CO₂ captured from the...
Cemex cement works will be used to produce biopetrol via microalgae, which are multiplied and transformed through daily treatment cycles. During the first phase of processing high-value nutrients like EPA and omega fatty acids will also be extracted from the biomass.

**Germany** possesses a large, advanced, chemical engineering industry, and other pockets exists in **UK, France and Italy** which suggests that CCU in chemicals production could be a promising route for European industrial innovation (see also Box 1). Although large deposits of olivine and serpentine exist in **Finland** and **Portugal**, there only a few major CO₂ emission sources located in these countries compared to e.g. Germany and the UK, meaning that transport of the minerals over long distances will likely be necessary for CO₂ mineralisation is to develop as a viable option for CCU in Europe.

The huge potential for geothermal energy generation in **Iceland** is also stimulating interest into the conversion of geothermal power combined with CO₂ into road transport fuels (Box 3).

**Box 3 - Renewable methanol production in Iceland**

Methanol is produced by reacting a hydrogen and CO₂ containing “syngas” in the presence of a copper, zinc oxide and alumina catalyst. Typically, syngas is produced through natural gas reforming. An alternative route to hydrogen production is electrolysis of brine, which – because of the large electricity requirement – is generally constrained to areas with surplus cheap electricity. To produce renewable methanol, the electricity must come from a renewable energy source, whilst a source of CO₂ is also necessary to provide carbon (in standard processes this is derived from the natural gas).

Because Iceland has abundant resources of geothermal energy, as well as brine resources, it is an ideal candidate for the production of renewable methanol. The concept is now being brought into commercial production by Carbon Recycling International (CRI), a venture capital backed Icelandic-American business based in Iceland, with offices in California.

CRI initially developed a pilot plant, which commenced operation in 2007, with support from the Icelandic New Technology Development Fund, and involving other research partners. The technology developed was based on production of hydrogen using electricity and CO₂ both supplied from geothermal power production. In late 2011, the George Olah Renewable Methanol Plant entered into operation, a commercial scale facility producing 2 million litres of renewable methanol per annum, with plans to expand to production to 5 million litres by the end of 2012. CRI has greater ambitions for the technology, with plans to construct a larger plant capable of producing 50 million litres per annum for export into European markets.

In general, renewable methanol production is economically viable where cheap and clean electricity is available and energy costs are high (for refined products). However, one of the challenging aspects is finding cheap renewable electricity in proximity to anthropogenic CO₂: the CO₂ used by CRI in Iceland is from volcanic/geothermal origins.

5.6 Rest of the world

The prospect of developing value-added applications for captured CO₂ has been a key element in garnering interest in CCS over recent years. This is evidenced in the transition in 2009 of the Major Economies Forum initiative on CCS to the Clean Energy Ministerial action group on CCUS – the “U” representing the addition of CO₂ utilisation to the scope of the group’s remit. This was essential to
brining in a wider group of members, and was instrumental in driving renewed interest in utilisation as per the recent study for the GCCSI (Parsons Brinkerhoff/GCCSI, 2011).

It has not been possible to undertake an exhaustive assessment of the scale of development of CCU activities in parts of the world outside of the EU, although some examples of activities are outlined below.

**CO₂ to fuels** – as highlighted in Table 3, there are a wide number of actors involved in the development of CO₂ to fuels, in particular within the US. In the US, a wide range of start-up companies are active across the CO₂ to fuels areas of R&D, although some have recently gone out of business such as GreenFuel Technologies. In other parts of the world, India is developing significant R&D activities in the area of CO₂ capture for use in algae cultivation, with a number of start-up companies emerging over recent years. In a recent announcement, Swiss cement maker Holcim announced a combined R&D project with ACC, The Indian Institute for Agricultural Research (IARI), The Indian Institute for Technology (Delhi) and the National Council for Building Materials India to couple CO₂ capture with algae growing at one its plants in India. The plan is to use the harvested biomass as a fuel for use in the kilns (Holcim, 2012). The Indian Institute of Technology is also working in conjunction with the University of Uppsala (Sweden) to develop suitable bioreactor configurations for algae growing. In China, the 11th Five Year Plan Science and Technology Programme is also engaged in research in to biodiesel production from algae grown with captured CO₂ (Li Jia, 2011), and plans further work under the 12th Five Year Plan, with research led by ENN Group and Jinan University in Inner Mongolia (MOST, 2011). The construction firm Qatari Diar also recently announced plans to construct an algae CO₂ sequestration project in North West Qatar (Construction Week Online, 2012).

**Enhanced commodity production** – several institutions in the US and Australia have been pioneering research into the use of CO₂ to enhanced geothermal energy cycles, primarily at the Sandia National Lab, University of Minnesota, and various start-up companies in Australia such as Origin Energy (see Table 3).

**Enhanced hydrocarbon recovery** – a wide number of countries outside of Europe are interested in developing CO₂-EOR technology, including the US (further development and increasing use of anthropogenic CO₂), countries in the Middle East, Egypt, China, countries in South East Asia such as Thailand, and India. Activities relating to CO₂-EGR and CO₂-ECBM recovery are less advanced.

**CO₂ mineralisation** – various research efforts into the use of CO₂ mineralisation processes are ongoing worldwide, principally driven by the potential to stabilise mine tailings rather than the generation of useable products. For example, Australia has been pioneering the use of CO₂ as a means to stabilise alkaline mine tailings produced during bauxite processing (known as “red mud”; see above). The technology has been tested and proven as an effective stabilisation technique for red mud at Alcoa’s Kwinana refinery in Western Australia. The South African Council for Geosciences has also undertaken extensive research into the role that mine tailings could play in storing CO₂ captured from various sources, principally coal-fired power plants, in the country (Doucet, 2011). However, no
plans to test the technology in South Africa have yet been announced. MacGill University in the US, under the US Department of Energy (DOE) and National Energy Technology Laboratory (NETL) has been examining the potential for use of CO₂ for concrete curing (NETL, 2011a). CSS Material Inc and Rutgers University in the US are also receiving DOE funding to explore the potential for the creation of a low-cost Portland cement substitute product derived from anthropogenic CO₂ (NETL, 2011b).

**Chemicals production** – In the US, Massachusetts Institute of Technology – in conjunction with Siemens – has been developing CO₂ utilisation technologies for the production of polymers, using funding from the US DOE, NETL CO₂ utilisation programme (NETL, 2011c). In China, the China National Offshore Oil Company (CNOOC) is currently developing a method of CO₂ manufacturing of biodegradable plastic in Dongfang, Hainan Province (MOST, 2011).
6 What could CCU technologies offer for various EU policy considerations?

A key component of the required analysis is the consideration of whether, and if so, how CCU technologies could contribute to key policies of the European Union. In Section 3 of Part 1, some of the factors driving greater interest in CCU were highlighted. In this section, these drivers are reviewed in more detail, and considered in the context of EU policy interests in the following areas:

- Climate action
- Energy security
- Industrial innovation

6.1 CCU and EU Climate Policy

The EU’s near-term climate policy is centred around the “20-20-20” target, which by 2020, aims to: reduce EU emissions by at least 20% below 1990 levels, for 20% of EU’s energy consumption to come from renewable resources, and; a 20% reduction in primary energy use compared with projected levels, to be achieved by improving energy efficiency. Over the longer-term, in its Roadmap to 2050 (European Commission, 2011b) the European Commission outlined a possible pathway to reduce GHG emissions in the Union by 80% against 1990 levels by 2050 – a position which supports international commitments under the United Nations Framework Convention on Climate Change. The possible sectoral contributions to this ambitious target are outlined below (Figure 3).

6.1.1 CCU reducing emissions

CCU technologies can play a part in achieving this goal. Permanent, or at least semi-permanent, emission reductions can be achieved by fixing carbon into products such as polymers and in mineralised form for use in e.g. construction materials. Technologies involving geological processes e.g. CO₂-EOR and EGSCO₂ also offer a pathway to long-term geological storage of CO₂. CCU technologies which lead to alternative forms of liquid fuels can substitute and displace conventional petroleum derived products e.g. renewable methanol. In addition, where alternative processes employing CCU technologies use less energy intensive conversion processes – or value chains – than conventional methods, secondary emission reductions can also be achieved through e.g. reduced electricity or fossil fuel consumption. Furthermore, using CO₂ as a working fluid in some applications can increase their energy use efficiency.
A key aspect of CCU technologies, as illustrated in Figure 3, is their capacity to contribute to emission reductions across many sectors of the economy: the oil & gas industry; the chemicals sector; transport; construction and power sectors can all benefit from emission reductions delivered through CCU technologies. These sectors are all critical to achieving the EU's long-term emission reduction pathway to 2050. For example:

- **The power sector** – decarbonising the power sector is a core theme of the EU Roadmap, with virtual elimination of emission of GHGs in the sector by 2050. As shown in the next section, CCU can support this by assisting the development of CCS technologies. In the near-term, CCU could help overcome barriers to CCS, therefore avoiding the risk of technology lock-in in the power generation across the Union, a key risk to achieving the Roadmap’s ambitions;

- **The transport sector** – new forms of biofuels are seen as critical to support emission reductions in transport, particularly for heavy trucks and aviation which have limited alternative means of propulsion. Renewable methanol and third generation biofuels from algae, fertilised by CO\textsubscript{2}, could be a major contributor to the long-term target. The EU has already set out its support framework for these types of technologies in its FP7 programme, where €20.5 M was allocated to three projects – BIOFAT, ALL Gas and InteSusAl (the “FP7 Algae Cluster”; see Box 2). As highlighted in Table 5, the potential future demand for CO\textsubscript{2} in
these applications could be high (> 300 MtCO₂/year), which will likely need to be sourced from the industrial sector if targets for decarbonisation of the power sector is successful.

- **The industry sector** – EU industry could become a key source of CO₂ for CCU applications in the future, if the power sector is to be fully decarbonised. Targets of 80% reduction could be supported through CCU applications, although the permanence of abatement – as reviewed next – will be an important consideration. Furthermore, CCU could be critical in the near-term to support longer-term objectives for deployment of CCS in industry (e.g. iron & steel; cement) from 2035 onwards.

A provisional attempt to map the various pathways through which CCU technologies can abate emissions of CO₂ to the atmosphere is shown in Figure 4 below. Because much of the information required to provide a more comprehensive or quantitative view is missing at the current time, the picture shown is partial and illustrative only.

![Figure 4 – Illustrative emission reduction pathways for CCU technologies](image_url)

The range of alternative pathways through which CCU technologies can abate CO₂ emissions also highlights the complexities involved in assessing the net emission reductions achieved by a particular
CCU technology. Important factors for consideration include: the boundaries for the assessment, the scope for leakage (i.e. emission changes occurring outside the immediate project boundary, but attributable to the activity or technology), and the permanence of the reductions achieved. These issues are considered from a regulatory perspective further in the sections below, where the challenges of incentive design and monitoring, reporting and verification are discussed.

Only very limited attempts to quantify the potential net benefits for CCU technologies have been made to date e.g. through the use of life-cycle analysis (LCA). It must be noted however, that these are typically based on only limited - and potentially unrepresentative - case studies. For example, case study LCA figures for a range of CCU applications undertaken by Edge Environment are presented in Parsons Brinckerhoff/GCCSI (2011). These figures present tonnes of CO₂ equivalent emitted in reusing each tonne of CO₂. They suggest that for many technologies these rates are significant and may therefore not result in net emission reduction benefits (e.g. >1 tCO₂ emitted/ 1 tCO₂ reused). However, the study notes that various factors have an important outcome on the LCA results, including, for example, assumptions made in relation to CO₂ capture (the case studies are predominately based on capture plant retrofitted to coal-fired power plant, with parasitic energy losses made up by fossil-fuel power generation) and the boundary definitions (e.g. for CO₂ concrete curing, 90% of the emissions associated with reuse are actually attributable to cement manufacturing, which would occur in the absence of CCU). As also noted in the study, a more appropriate approach to quantifying potential net benefits would involve comparing life-cycle emissions from products produced via a CO₂ reuse pathway with those produced by conventional pathways; this type of research has yet to be undertaken.

The evidence base concerning the potential GHG benefits from CCU applications is currently very limited, and there is clearly a strong need to build on the limited analysis undertaken to date. Notwithstanding the uncertainty around the specific potential, there is a clear case that several CCU technologies can play a part in reducing emissions. Additionally, the scope for CCU to support CCS as a climate change mitigation technique is also an important potential contribution of CCU in reducing emissions, as described further below.

### 6.1.2 CCU supporting CCS

The potential role of CCS in reducing global emissions of greenhouse gas to the atmosphere was set out by the International Energy Agency (IEA) in 2009. Its CCS Roadmap highlighted that, as part of a cost-optimised set of global GHG abatement options, by 2020 around 300 MtCO₂ per year could be captured by 100 CCS projects around the world. In the EU, when the Commission developed its initial framework for support for CCS in Europe, culminating in the 2009 Directive on the geological storage of CO₂, the vision was for CCS to contribute around 7 MtCO₂ abatement by 2020, and reaching 160 MtCO₂ by 2030 (European Commission, 2008b).

---

Presently, however, there is growing realisation that this target will be hard to reach under prevailing economic conditions, augmented by ongoing challenges in providing sustainable means of financial support for the operation of CCS plants e.g. due to the lack of a suitably high and stable carbon price in the EU carbon market. The GCCSI reported in its latest status report (GCCSI, 2012) that over the period 2011-12, only 2 new CCS projects (8 in total) moved to the Execute phase (i.e. passed final investment decision), whilst several others were cancelled or are presently undergoing reappraisal. In many cases – in particular in Europe – one of the main reasons for this has been a lack of confidence by project developers in the long-term economic support for CCS projects. In the EU, the NER300 programme originally envisioned to raise in excess of €4 billion to support CCS and new forms of renewable energy, although the depressed EU carbon market has seen only €1.14 billion raised by the sale of 66% of the NER300 (i.e. 200 million EUAs) in the first tranche of NER300 capitalisation. Although a second tranche will be sold in 2013, the funds raised could be less than €2 billion, which must be spread across 8 projects recently shortlisted by Commission; potentially only about €250 million per project. At least one of the projects in the NER300 shortlist – Don Valley Power – will include CO₂-EOR as a means of raising additional revenue for project support. As of December 2012, despite the NER300 monies being available for CCS projects in the EU, the Commission announced that no CCS projects would be financed under the first phase of the programme due to a lack of suitable candidates or secured Member State co-funding (European Commission, 2012a).

In other jurisdictions – in particular the United States – emergent proposals for CCS projects are tending to be brought forward in conjunction with CO₂-EOR so as to provide some means to enhance project economics. Similarly, most international initiatives linked to CCS, such as the Clean Energy Ministerial and the Carbon Sequestration Leadership Forum, are increasingly shifting the scope of their focus to also include CCU alongside CCS (or “CCUS”).

Furthermore, in some European countries – in particular Germany – institutionalised barriers have persisted to prevent the uptake of CCS, partly linked to public resistance to the technology, in particular the geological storage of CO₂. In others, local action has led to problems in project development. In Germany, such resistance has manifested itself in a lack of will amongst many regional governments (Lander) to support the transposition of the EU CCS Directive into national law, thus prohibiting the geological storage of CO₂ within the country. ¹² The uncertainty has led to the cancellation and delay of the Jänschwalde and Alkmar projects respectively, whilst public acceptance led to the cancellation of the Barendrecht project in the Netherlands.

As a result, policy-makers in all jurisdictions are being forced to consider alternative means by which CO₂ capture from energy and industrial emissions may be promoted, with CCU potentially offering a more publically acceptable and financially viable solution.

¹² A draft bill was approved by the Bundestag (Parliament) in July 2011, but subsequently rejected by the Bundesrat and has been residing with the Mediation Committee, although a new compromise was accepted by the Bundestag in July 2012 and the amendments are expected to be accepted by the Bundesrat in due course.
6.2 CCU enhancing energy security

Presently over half of the EU’s energy supply is sourced from third countries outside of the EU: over 80% of oil, 60% of gas and over 95% of uranium. The EU Climate Change Roadmap to 2050 (European Commission, 2011c) highlights the issues associated with dependency on imports of fossil fuels from outside the EU. Reducing this dependence through transformation of the power, industry, buildings and transport sector could reduce average fuel costs by between €175 billion and €320 billion per year over the next 40 years or so. Over this period, it estimates that the import of oil could half from present levels. The current situation leaves the EU vulnerable to disruptions in its energy supply due to various reasons, including increased international competition in sourcing fossil fuel supplies around the world, increasing price fluctuations, and technical and political disruptions in supplier and transit countries. The Roadmap also suggests how transformation of the current energy supply system will require an acceleration of energy efficiency measures, increasing the supply and demand for renewable energy, and the development of smart technology, storage and alternative fuels. These aims are supported by a framework of key energy policies including the Renewable Energy Directive (RED) and the Energy Efficiency Directive. Ensuring security of energy supply is highlighted as a key energy policy goal and one that is aligned with the aims of increasing energy efficiency, renewable energy and smart technology, energy storage and alternative fuels.

As outlined previously, several technologies involving CCU offer means to enhance energy supply from indigenous and renewable resources. Technologies where CO$_2$ is used to enhance hydrocarbon recovery, such as enhanced oil recovery and enhanced gas recovery (EGR) can help to extend the life of national hydrocarbon assets, reducing reliance on imported fuels. Alternatively, enhanced coal bed methane recovery (ECBM) can provide new sources of fossil fuels in some regions.

Other CCU technologies can be used to provide energy storage or enhance the performance of existing energy generation systems. For example, captured CO$_2$ may be used as a form of energy storage through its synthesis with hydrogen so as to produce methane or methanol, potentially providing a useful source of off-peak demand in systems dominated by renewables such as geothermal or wind. Its use in the production of formic acid via hydrogenation over various catalysts can also provide the same type of interim energy storage. CO$_2$ may also be used as a working fluid in geothermal power systems, or as a replacement for water/steam in conventional power cycles, enhancing overall system performance.

In addition, captured CO$_2$ could be bubbled through algae cultivation ponds to accelerate their growth, potentially providing an important future contribution to third generation biofuels production.

Presently the role of CCU in enhancing supply security has not been seriously considered, but clearly certain technologies offer significant potential.
6.3 CCU supporting industrial innovation

A continuing theme of EU policy relating to climate change is the innovation and job creation that would be driven by such structural changes in energy supply, in both the short- and medium-term. The EU’s strategy for growth has highlighted that presently Europe is investing 0.8% of GDP less than the US, and 1.5% less than Japan, in research and development (R&D). The “Innovation Union” – part of the EC’s Europe 2020 growth initiative – includes industrial innovation as a key part of sustainable growth, with the objective of increasing R&D investment and innovation spending to 3% of GDP by that year. The creation of new products, new value chains and more efficient use of resources forms a key part of the future industrial strategy for Europe, all of which is seen as a key element of keeping the EU competitive through the ongoing period of increasing globalisation.

To achieve this, the innovation process must involve taking the work of world-leading networks of research institutions present in Europe and turning these efforts into commercially viable and globally relevant technology applications. There are a number of factors involved in achieving this aim including:

- Promoting excellence in education and skills development;
- Improving research partnerships and collaboration;
- Creating a single innovation market (ensuring that “Europe doesn’t replicate the same thing 27 times across the Union”);
- Pooling resources to maximise leverage of the knowledge and skills base;
- Focussing funding on innovation priority areas;
- Enhancing access to capital for innovative companies;

At present, in terms of the key indicators for innovation success – R&D spending, presence of world leading universities, percentage of the population with advanced university degrees etc – the EU is falling behind other parts of the world such as the US and Japan and is rapidly being caught up by emerging economies, in particular China (European Union, 2011a).

Clearly the factors highlighted for successful innovation – and the performance of Europe against such key indicators – are generic issues across a wide range of sectors, products and services present in the EU; applications involving CCU will form just small component of innovation developments going forward. On the other hand, new areas of technological development driven by macro-economic trends and global societal challenges, such as innovation in energy systems and climate change mitigation are key drivers for economic growth and as such can form a cornerstone of broad innovation policy. But even in the key area of climate change mitigation, where the EU has consistently sought to act as a leader in innovation through the establishment of policy measures such as the EU ETS, the region is falling behind competitor countries, in particular Japan in developing such a technology lead. For example, data suggest that Japan filed more than twice as many patents for climate mitigation technologies as the EU in 2007 (European Union, 2011b).

---

13 Example measures drawn from EU Innovation Union website at: [www.ec.europa.eu/research/innovation-union](http://www.ec.europa.eu/research/innovation-union)
On this basis, CCU technologies can form an integral part of a growth and innovation strategy for Europe, as evidenced in the previous sections of this report.

Increasing numbers of industrial applications for CO₂ are under development across different Member States of the EU, primarily in the chemicals industry, but also in other sectors where mineralisation into building materials or other applications based on CO₂ mineralisation are under development. The use of CO₂ to cultivate algae, and the potential uses of lipids and other products derived from algae are extremely large, such as pharmaceuticals and nutraceuticals. All these technologies have the potential to contribute to Europe's growth strategy – promoting innovation in production, reducing waste, enhancing resource efficiency, reducing dependence on imports (e.g. through the use of CO₂ as an alternative to petrochemicals as a source of carbon in chemicals production), creating jobs and developing export markets for goods, services and expertise. For this reason, efforts to promote and develop these technologies can form a key part of Europe's R&D policies and innovation strategy over the next 10-20 years or so.
Part 2:
TAKING ACTION TO SUPPORT CO₂ REUSE
1 Introduction

This Part of the Report builds on the issues highlighted in Part 1 by identifying specific actions that may be taken in the EU to support further development in CCU technologies. The objective is threefold: to identify what is needed to stimulate the development of CCU technologies, identify implications of CCU development on existing policy framework and formulation of recommendations for policies and regulations to support the development of CCU technologies. This requires a more in-depth analysis of the status and development of CCU and therefore a selection of CCU technologies is made. For these technologies their current development status is determined by performing an innovation analysis, using the Functions of Innovation System as an analytical framework (Hekkert et al., 2007). The framework includes seven sets of activities (or functions) that must be performed to develop the technology from research to commercial implementation. The development and performance of these functions is checked among technology developers by conducting interviews. Based on the analysis the current development status of the technologies can be determined as well as what is needed to stimulate the development. For these identified needs recommendations for policies and regulations are formulated.

As identified in Part 1, CCU technologies can have implications on existing European Climate Action policies. Conversely, policy measures implemented to achieve the formulated targets on European Climate Action policies also have implications for the development of CCU technologies. The approach taken is as follows:

- Section 1 discusses the basis for selecting the most appropriate technologies which could be taken forward in Europe. A set of six selection criteria is described and the resulting selection of CCU technologies is presented.
- Section 2, building on Part 1, provides a more detailed review of the current development status of the selected technologies and what is needed to stimulate this. The information needed to perform this analysis is provided by literature research, dedicated interviews, stakeholder discussions, workshop results and an additional questionnaire. This section will provide the basis for the formulation of recommendations for policy and regulations to stimulate the development of CCU technologies.
- Section 3 includes an assessment of the impacts of supporting CCU on current EU policies. This is done for existing policies and regulations on industrial innovation, energy security and climate action.
- Section 4 provides a summary, conclusions and recommendations.
2 Needs for and barriers to CCU development

To get a clear view on the development needs of CCU technologies and how this can be stimulated, an in-depth analysis of CCU technologies has been performed to a selection of (categories) of CCU technologies.

Analysing the technologies lead to a better understanding of the current development status, needs and barriers, and how the development can be stimulated. To obtain these insights, an analytical framework based on innovation theory is suggested. Performance of the “innovation analysis” leads to two results:

- The current status of the technological development;
- Identification of needs to stimulate the development.

The innovation analysis requires specific information, which can be partly obtained from literature, websites and reports, but also requires interviews with people involved in the development of the CCU technologies. The focus of the interviews is on:

- Identification of the challenges faced in the development of the technology;
- Identification of gaps and needs to stimulate the development;
- Evaluation of the performance of individual innovation functions;
- Identification of policies and regulations to stimulate the development.

The aim of this section is to provide an overview of the needs and barriers of CCU technologies creating a basis on which measures to stimulate and accelerate technology development are formulated. Section 2.1 describes the innovation framework and underlying theories. Section 2.2 provides a selection of CCU technologies for in-depth analysis. The CCU technologies needs and barriers identified through the innovation analysis are described in the section 2.3. Based on the outcomes stimulation measures are formulated (section 2.4). Annex A gives an overview of the questionnaires.

2.1 Innovation analysis framework

The development of technologies involves a broad variety of aspects and activities that have to be addressed and performed to successfully develop an idea or invention to a commercially implemented product. Examples of activities are executing R&D-projects, acquiring funding and introduction of the technologies in markets. According to the Functions of Innovation Systems framework (Hekkert et al., 2007) seven sets of activities or – as referred to in the theory – functions are focusing on specific aspect of technological development. Technological development can be divided into two parts: the "hard" technological part and the "soft" institutional part. The technical part requires development of knowledge (e.g. learning by research), experience (e.g. learning by doing) and knowledge diffusion.
(e.g. by learning from each other). Activities related to resource mobilisation (e.g. is there enough funding to develop the technology?) are used to fund the technological development. The institutional part focuses on embedding the technology into society addressing issues such as guidance (e.g. what are the expectations of the technology? Is the technology contributing to reach targets?), market development (e.g. what is done to stimulate competition with incumbent technologies?) and creation of legitimacy (e.g. is there opposition against the technology and how can this be addressed?). A more profound description of the innovation functions is shown in Box 4.

### Box 4 - Functions of innovation systems

The following seven innovation functions are distinguished:

**Function 1: Entrepreneurial activity** – activities from companies that are interested in a technology, because they see business potential. Indicators: number and scale of demonstration projects, timeframe to deployment and total demand;

**Function 2: Knowledge development** – creation of knowledge that contribute to the development of technologies. Indicators: the role of knowledge creation in the development process and type of knowledge created (fundamental or practical);

**Function 3: Knowledge diffusion** – by sharing knowledge and expertise a better understanding is gained in the technology. Indicators: ways of knowledge diffusion (conferences or workshops) and the background of participants (knowledge institutions or companies);

**Function 4: Guidance of the search** – the development of a technology is influenced by opinions from experts and politicians, expectations and economical / political sentiment. Indicators: what are the expectation until 2050 (see task 2) and the support for the technology from experts and politicians (favourable solution);

**Function 5: Market creation** – to gain a market share most (renewable) energy technologies must compete with incumbent technologies. Government can stimulate the emerging technologies by creating special market conditions. Indicators: commercial viability and the willingness of governments to create market conditions;

**Function 6: Resource mobilisation** – resources are needed to stimulate technological development. These resources can be both financial and human. Indicators: the extent to which the development of the technologies relies on external funding, obtaining an overview of the current and planned public and private support for reuse technologies, is funding needed and can emerging technologies apply for funding via existing instruments;

**Function 7: Creation of legitimacy** – emerging technologies often have to cope with resistance to change. By identifying this in an early stadium, action can be taken to prevent unnecessary delay and problems. Indicators: how favourable is the technology, additional CO2 emissions from reuse, identification of opposition against the use of the technology and lobby activities pro or against the technology.

Based on the paper Functions of innovation systems: a new approach for analysing technological change (Hekkert et al., 2007)

Good performance of the functions creates conditions in which a technology can develop well. The development of individual functions also gives information on the focus and status of the technological development. If the development is still in an early phase, most attention will be on the technical functions such as knowledge development (function 2), while if technologies are close to commercial availability focus will be more on the institutional functions such as market creation (function 5) and creation of legitimacy (function 7). An evaluation of these activities will obtain
insights in the current development status of technologies. To determine the needs for further development, the analysis focuses on the different aspects - or sometimes indicated as - functions of technological development.

2.2 Selection of CCU technologies for in-depth analysis

As outlined in Part 1, the term CCU can be applied to a wide range of diverse technologies and applications, each at various stages of development and commercialisation. Although there is uncertainty regarding the potential benefits some of these options may offer over the coming decades (e.g. type and scale), clearly some could play a more important role than others in helping to support key EU policy objectives. Drawing on the issues highlighted in Part 1, the following criteria have been used to select the most appropriate CCU technologies for further consideration in an EU context:

- Uptake potential
- Economic potential
- Applicability to the EU
- Potential for GHG abatement
- Environmental, health and safety considerations
- Alignment with EU energy policy

Annex B provides a detailed elaboration of the criteria.

Using the abovementioned criteria and the information set out in Part 1 of this report, a selection of the most interesting technologies in a European context has been made. As shown in Table 7; each of the identified CCU technologies has been assessed, where green indicates that the desired selection criteria is met; amber indicates that it may be potentially or partially met, and red that it is not met.

Six technologies are seen to be in close alignment with the described criteria. The production of renewable methanol is considered to have significant uptake potential through its potential use as an alternative liquid fuel in European markets, and also has potential GHG abatement benefits subject to further process efficiency improvements. Despite facing significant economic and market challenges, formic acid production has a similarly large uptake and GHG abatement potential, particularly over the longer term subject to the development of the hydrogen energy market. Algae cultivation from one or more processes currently under development has the potential to utilise large volumes of CO₂ in the creation of multiple products, most noticeably alternative fuels and chemicals, while mineralisation technologies such as CO₂ concrete curing and carbonate mineralisation (both cement and other) could offer important alternatives to existing industrial products with attendant CO₂ storage benefits. Within the chemicals sector, the use of CO₂ in the synthesis of polymers could create new value added commercial products, resulting in potential GHG reductions whilst leveraging key existing skills and expertise across European industry.

Other CCU technologies and applications may also have considerable benefits in terms of energy, industry innovation and climate action. However, for some of these (e.g. urea and conventional
methanol yield boosting) the scale of their uptake potential and applicability to the EU is likely to be relatively limited, whereas for others there is at present insufficient information regarding their potential commercial viability or benefits - largely due to their current early stage of development and demonstration (e.g. photocatalytic reduction, helioculture, CO₂-enhanced gas recovery).
<table>
<thead>
<tr>
<th>CCU technology</th>
<th>Technology or application</th>
<th>Selection criteria</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th>Selection?</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Uptake potential</td>
<td>Economic potential</td>
<td>EU applicability</td>
<td>Abatement potential</td>
<td>EHS concerns</td>
<td></td>
</tr>
<tr>
<td>CO₂ to fuels</td>
<td>Renewable methanol production</td>
<td>High</td>
<td>Moderate</td>
<td>Significant</td>
<td>Pot. significant</td>
<td>None known</td>
<td>Positive</td>
</tr>
<tr>
<td></td>
<td>Formic acid production</td>
<td>Very high</td>
<td>Uncertain</td>
<td>Significant</td>
<td>Pot. significant</td>
<td>None known</td>
<td>Positive</td>
</tr>
<tr>
<td></td>
<td>Algae cultivation</td>
<td>Very high</td>
<td>Uncertain</td>
<td>Significant</td>
<td>Pot. significant</td>
<td>Pot. concerns</td>
<td>Positive</td>
</tr>
<tr>
<td></td>
<td>Helioculture</td>
<td>High</td>
<td>Unknown</td>
<td>Pot. significant</td>
<td>Unknown</td>
<td>None known</td>
<td>Positive</td>
</tr>
<tr>
<td></td>
<td>CR5</td>
<td>Potentially high</td>
<td>Unknown</td>
<td>Pot. significant</td>
<td>Unknown</td>
<td>None known</td>
<td>Positive</td>
</tr>
<tr>
<td></td>
<td>Photocatalytic reduction of CO₂</td>
<td>High</td>
<td>Unknown</td>
<td>Pot. significant</td>
<td>Unknown</td>
<td>None known</td>
<td>Positive</td>
</tr>
<tr>
<td></td>
<td>Nanomaterial catalysts</td>
<td>High</td>
<td>Unknown</td>
<td>Pot. significant</td>
<td>Unknown</td>
<td>None known</td>
<td>Positive</td>
</tr>
<tr>
<td>Enhanced commodity productions</td>
<td>EGS with CO₂</td>
<td>Likely moderate</td>
<td>Uncertain</td>
<td>Likely moderate</td>
<td>Highly variable</td>
<td>Not significant</td>
<td>Moderate</td>
</tr>
<tr>
<td></td>
<td>Supercritical CO₂ power cycles</td>
<td>Potentially high</td>
<td>Unknown</td>
<td>Significant</td>
<td>Moderate</td>
<td>None known</td>
<td>Moderate</td>
</tr>
<tr>
<td></td>
<td>Urea yield boosting</td>
<td>Moderate</td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
<td>None known</td>
<td>Moderate</td>
</tr>
<tr>
<td></td>
<td>Methanol yield boosting</td>
<td>Moderate</td>
<td>Low</td>
<td>Low</td>
<td>Moderate</td>
<td>None known</td>
<td>Moderate</td>
</tr>
<tr>
<td>Enhanced hydrocarbon recovery</td>
<td>Enhanced oil recovery</td>
<td>Highly uncertain</td>
<td>Highly variable</td>
<td>Moderate</td>
<td>Pot. significant</td>
<td>Not significant</td>
<td>Positive</td>
</tr>
<tr>
<td></td>
<td>Enhanced gas recovery</td>
<td>Moderate</td>
<td>Low</td>
<td>Low</td>
<td>Pot.</td>
<td>None known</td>
<td>Positive</td>
</tr>
<tr>
<td>CO₂ mineralisation</td>
<td>Enhanced coal bed methane (ECBM)</td>
<td>Carbonate mineralisation (cement)</td>
<td>Sodium bicarbonate</td>
<td>CO₂ concrete curing</td>
<td>Bauxite residue carbonation</td>
<td>Carbonate mineralisation (other)</td>
<td>Chemicals production</td>
</tr>
<tr>
<td>--------------------</td>
<td>----------------------------------</td>
<td>----------------------------------</td>
<td>-------------------</td>
<td>--------------------</td>
<td>--------------------------</td>
<td>-------------------------------</td>
<td>----------------------</td>
</tr>
<tr>
<td></td>
<td>Low</td>
<td>High</td>
<td>Pot. high</td>
<td>Moderate</td>
<td>Low</td>
<td>High</td>
<td>Positive</td>
</tr>
<tr>
<td></td>
<td>Highly variable</td>
<td>Uncertain</td>
<td>Significant</td>
<td>High</td>
<td>Moderate</td>
<td>Pot. significant</td>
<td>Positive</td>
</tr>
<tr>
<td></td>
<td>Likely moderate</td>
<td>Pot. significant</td>
<td>Signficant</td>
<td>Moderate</td>
<td>None known</td>
<td>Moderate</td>
<td>YES</td>
</tr>
<tr>
<td></td>
<td>Pot. significant</td>
<td>High</td>
<td>None known</td>
<td>Moderate</td>
<td>Unclear</td>
<td>Moderate</td>
<td>NO</td>
</tr>
<tr>
<td></td>
<td>Pot. concerns</td>
<td>High</td>
<td>Significant</td>
<td>None known</td>
<td>Positive</td>
<td>Not significant</td>
<td>YES</td>
</tr>
<tr>
<td></td>
<td>Positive</td>
<td>None known</td>
<td>Unknown</td>
<td>None known</td>
<td>Positive</td>
<td>Positive</td>
<td>YES</td>
</tr>
<tr>
<td></td>
<td>NO</td>
<td>None known</td>
<td>Unknown</td>
<td>Unknown</td>
<td>No</td>
<td>NO</td>
<td>NO</td>
</tr>
</tbody>
</table>
2.3 Innovation assessment to CCU needs, barriers and drivers

This section shows the results of the innovation analysis performed on the selected technologies. This session describes:

- An innovation function analysis per technology – this includes the evaluation of the individual functions for each technology. This assessment gives information on the current development status;
- The identified needs, barriers and drivers – for each technology an overview is made listing the needs, barriers and drivers. The needs and barriers form important input for the formulation of stimulation measures and the recommendations;
- General findings with respect to technology and market development for the selected CCU technologies.

Annex C provides an extended description on the development of the selected technologies.

2.3.1 Renewable methanol

Activities in the development of renewable methanol include all innovation functions. Renewable methanol is already commercially available in Iceland. Here the production of renewable methanol using geothermal energy is developed by Carbon Recycling International (CRI) (function 1). New possibilities combining gasification of waste with CO₂ utilisation and the use of intermittent energy sources, such as wind and solar, for the production of methanol are being assessed (function 2). These activities are approaching pilot-scale demonstrations. The usage of intermittent energy sources to produce renewable methanol could lead to the use of methanol as a storage medium for renewable energy. This would open up new possibilities (function 4). Worldwide, only a few companies are currently focussing on renewable methanol. CRI cooperates in Europe with other (local) organisations on the development of renewable methanol, but they would like to see more organisations involved (function 3). Although already commercially available in Iceland, expansion towards the rest of Europe seems difficult. Although renewable methanol can be used by Member States to achieve renewable energy targets on transportation fuels, most Member States are focussing on biofuels. This reduces the willingness of Member States to stimulate the use of non-bio alternatives, such as renewable methanol. Another (future) barrier is the 3% blending rate. Technically it is possible to increase the blending rate, which would offer a greater potential for renewable methanol (function 5). So far, there are no experiences with public opposition against renewable methanol (function 7). Remarkably, CRI developed their business without the support of European funds (function 6).
Table 8 - Needs, barriers and drivers for renewable methanol

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Needs</strong></td>
</tr>
<tr>
<td>• Increasing the European market potential for renewable methanol;</td>
</tr>
<tr>
<td>• Increase in R&amp;D activities to develop renewable methanol production using intermittent renewable energy sources and gasification of waste.</td>
</tr>
<tr>
<td><strong>Barriers</strong></td>
</tr>
<tr>
<td>• Current biofuel mandates are sufficient to meet renewable energy targets in transportation fuels and therefore there is no incentive to use renewable methanol;</td>
</tr>
<tr>
<td>• Blending rates are limited to 3%, while technically it could be increased;</td>
</tr>
<tr>
<td>• Limited amount of technology developers and lack of competition.</td>
</tr>
<tr>
<td><strong>Drivers</strong></td>
</tr>
<tr>
<td>• The potential use of renewable methanol as an energy storage medium for intermittent renewable energy sources.</td>
</tr>
</tbody>
</table>

2.3.2 Formic acid production

The current focus in the development of formic acid production is on knowledge development (function 2). In the development of the technology, different types of stakeholders are involved, among which some industrial companies (function 1). Two of the larger projects that are developing formic acid production are ECFORM (DNV) and CO2rect (including Bayer, RWE and Siemens). The next step in the development would be demonstration projects.

Formic acid production can potentially be used as storage medium for hydrogen and therefore possibly stimulating the developments towards a hydrogen economy (function 4).

There are almost no activities on market creation (function 5), and creation of legitimacy (function 7) as the development is still in an early stage.

Table 9 - Needs, barriers and drivers for formic acid production

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Needs</strong></td>
</tr>
<tr>
<td>• Increased effort in R&amp;D is needed, especially on:</td>
</tr>
<tr>
<td>o Catalysts life;</td>
</tr>
<tr>
<td>o Reduce energy consumption;</td>
</tr>
<tr>
<td>o Increase production rate;</td>
</tr>
<tr>
<td>• Funding to support demonstration projects;</td>
</tr>
<tr>
<td>• Increased involvement of industrial organisations;</td>
</tr>
<tr>
<td>• Incentives to mobilise more entrepreneurs towards the development CCU technologies, such as:</td>
</tr>
<tr>
<td>o Higher carbon price;</td>
</tr>
<tr>
<td>o Regulatory requirements to reduce carbon footprints;</td>
</tr>
<tr>
<td>• An integrated platform for CO2 utilisation and/or specific attention for CCU technologies as an independent research area.</td>
</tr>
<tr>
<td><strong>Barriers</strong></td>
</tr>
<tr>
<td>• No specific barriers in the development of the technology were mentioned.</td>
</tr>
<tr>
<td><strong>Drivers</strong></td>
</tr>
<tr>
<td>• No specific drivers in the development of the technology were mentioned.</td>
</tr>
</tbody>
</table>
2.3.3 Algae cultivation

Several projects are performed to develop algae cultivation in Europe. Most of the activities are focused on the development of R&D and demonstration projects (function 2). A variety of stakeholders is included in the development among which academics and industrial organisations (function 1). The algae community is active in organising knowledge exchange in the form of conferences and workshops. Collaborations become less common as intellectual property (IP) issues become increasingly important in this stage of the development. Exceptions are collaborations on larger projects e.g. under FP7 (function 3).

Projects that are deployed over the years required quite significant investments from governments and companies. The three projects developed under the Algae Cluster (FP7 projects) received in total € 31 million from the EU and a similar investment from private organisations and national governments (function 6). The expectations on the potential and the role that algae can play in the future as source for fuels, food and chemistry differ among stakeholders. Positive expert judgements can be a stimulus for interests in the technology and therefore become an important driver for more developments in R&D and demonstrations (function 4).

There is relatively less activity in market creation and creation of legitimacy in Europe (function 7). Compared to North America and Asia, the market for algae is relatively small. This is mostly for the use of algae for food. In other markets, algae are more common. It was noticed by one of the stakeholders that authorisation processes of algae species used for food are complex, which can slow down market creation (function 5).

<table>
<thead>
<tr>
<th>Table 10 – Needs, barriers and drivers for algae cultivation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Description</strong></td>
</tr>
<tr>
<td>Needs</td>
</tr>
<tr>
<td>• R&amp;D to increase bioconversion rates, improve scalability and to make technology floatable;</td>
</tr>
<tr>
<td>• Demonstrations projects to bring down cost price.</td>
</tr>
<tr>
<td>Barriers</td>
</tr>
<tr>
<td>• Authorisation of new algae species is indicated as complex.</td>
</tr>
<tr>
<td>Drivers</td>
</tr>
<tr>
<td>• Collaboration is stimulated by the EC, through FP7 projects;</td>
</tr>
<tr>
<td>• When built on marginal land, algae farms would not directly compete with other forms of biomass that need nutrient ground.</td>
</tr>
</tbody>
</table>

2.3.4 Cement production

Most of the activities are focused on scaling up projects to commercial-scale demonstration projects (function 2). Expectations are that the technology will become commercially available in about 5 years (Parsons Brinckerhoff/GCCSI, 2011). Most of the knowledge and technologies is developed outside of Europe, by companies such as Calera (USA) and Calix (Australia). These companies are focusing on commercial implementation of the technology (function 1). Novacem was one of the few European corporates that was actively involved in the development of carbon negative cement, but...
went bankrupt end of 2012 (function 1). That might be the cause for less activity on the implementation of CO₂ reuse alternatives in cement production. Currently, there is more focus on developing new technologies to produce eco-efficient cement, as for instance in the FP7 project “Eco-cement”.

So far, not much is known about market creation for CCU in cement production. As the cement industry is included in ETS this could act as a driver for incorporating the technology in cement production technologies (function 5). Also the large potential for CO₂ reduction for this specific technology - the global cement industry is responsible for 5% of the annual CO₂ emissions – can function as a driver for the development of the technologies (function 4). In the Eco-cement project institutes, universities and companies are collaborating, but the consortium does not include cement producers (function 3).

As mentioned, the technologies are mostly developed outside Europe and subsequently most of the resources as well (function 6). Calera has been sponsored by the United States Department of Energy in 2010 for nearly $20 million (USAToday, 2010). The efforts of UK company Novacem did also result in considerable funding (about £4 million), but it was not enough for Novacem to survive (IPPR, 2011; Novacem, 2012). One of the reasons is that potential investors are reluctant because of long payback period, which has an effect on the progress made in technological development (IPPR, 2012).

<table>
<thead>
<tr>
<th>Table 11 - Needs, barriers and drivers for cement production</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Needs</strong>&lt;br&gt;  - Technologies need to be demonstrated at a large-scale;&lt;br&gt;  - Products need to be adopted by cement producers and developed towards commercial maturity.</td>
</tr>
<tr>
<td><strong>Barriers</strong>&lt;br&gt;  - Investors are reluctant to invest as payback periods are long;&lt;br&gt;  - New forms of cement require testing and validation of its properties before it is accepted in the market.</td>
</tr>
<tr>
<td><strong>Drivers</strong>&lt;br&gt;  - The cement industry is a large emitter of CO₂ offering a great potential on reducing CO₂.</td>
</tr>
</tbody>
</table>

### 2.3.5 Carbonate mineralisation (other)

The activities around the development of carbonate mineralisation are characterised by fundamental research and the development of pilot-scale demonstration projects (function 2). Projects are focusing on feasibility of the technology and first assessments of the use of the resulting material are made. In these projects mostly academic institutions are actively involved (function 1).

The potential for carbonate mineralisation for CO₂ abatement is quite high, but the speed of the process must be improved considerably to make it commercially feasible. The resulting product could be used as a building material and possibilities are already being assessed in Singapore (function 4).
The availability of funds to stimulate R&D are limited (function 6). At this stage of the development there is not much attention for market creation (function 5), creation of legitimacy (function 7) and guidance of the search (function 4).

**Table 12 - Needs, barriers and drivers for other carbonate mineralisation**

<table>
<thead>
<tr>
<th>Description</th>
<th>Needs</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Improve the speed of the process from a hundreds kilos/hour-scale towards kton/hour-scale;</td>
<td>• The availability and the location of minerals are not always matching with the location of CO₂ point sources;</td>
</tr>
<tr>
<td>• Funding is needed, especially for demonstration projects.</td>
<td>• There are no significant commercial benefits of the product.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Drivers</th>
<th>Drivers</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Carbonate mineralisation offers a permanent storage option;</td>
<td>• Carbonate mineralisation offers a permanent storage option;</td>
</tr>
<tr>
<td>• The potential for CO₂ abatement is high.</td>
<td>• The potential for CO₂ abatement is high.</td>
</tr>
</tbody>
</table>

### 2.3.6 Polymer processing

Most of the current activities are focused on R&D, pilot projects and preparations for the demonstration phase (function 2). Several industrial organisations, among which Bayer and BASF, are involved in these projects (function 1). To lower the costs of the production process, demonstration projects and additional R&D efforts are needed. Stakeholders expect that CO₂ can become an important resource for the chemical industry in the future (function 4).

In the current projects, different types of stakeholders are collaborating, including academia, research institutes and (large) chemical companies. There are some specific conferences on CO₂ and polymers organised in Essen and Lyon (function 3).

Stakeholders do not expect any problems with public perception of CCU in polymers, as long as it is verifiable and the communication on this topic remains open. Moreover, producers are positive about the potential effect CO₂ reuse has on the polymers, as they offer an environmental-friendly alternative. To make these CO₂ reuse alternatives visible, developers would prefer to incorporation in existing labelling systems.

Some developers would like to see an active role of the European Commission in coordinating communication on CCU-products or on implementing instruments such as labelling, trade-marks and ISO certification (function 7).
Table 13 - Needs, barriers and drivers for polymer production

<table>
<thead>
<tr>
<th></th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Needs</td>
<td>• Financial support for demonstration projects;</td>
</tr>
<tr>
<td></td>
<td>• Recognition of CO\textsubscript{2} reuse under green labels.</td>
</tr>
<tr>
<td>Barriers</td>
<td>• No specific barriers in the development of the technology were mentioned.</td>
</tr>
<tr>
<td>Drivers</td>
<td>• The development of two large consortia to develop the technology, including large chemical companies;</td>
</tr>
<tr>
<td></td>
<td>• CO\textsubscript{2} can become an important resource for the chemical industry in the future.</td>
</tr>
</tbody>
</table>

2.4 General findings

The previous section has identified and listed needs, barriers and drivers for each of the CCU technology. In this section this has been compiled into generic needs and barriers:

- Many technologies are on the brink of the “Valley of Death”, the point in the development of the technology from a concept towards a commercial product. This important step towards commercialisation requires significant investments and willingness to take risks of industrial organisations. Before taking this step, entrepreneurs are searching for ways to lower risk and uncertainty on the one hand and optimising chances for commercial success on the other hand. This can be stimulated by making funds available for demonstration projects (technology push) or to create favourable market conditions (technology pull).
- CCU technologies could benefit when acknowledged as a separate research area. This could increase funding opportunities in R&D stimulation programmes such as Horizon 2020 and would accelerate the development of the technologies.
- Effects of CCU on themes like environment, energy supply and employment should be made visible and tangible for each technology. As an example, often it is not clear what the net effect of CCU technologies is on CO\textsubscript{2} emission reduction. It is therefore important that an LCA-like methodology is being developed and approved to get insights in the CO\textsubscript{2} balance of each of the technologies / products.
- Strong financial incentives to reduce CO\textsubscript{2} would be helpful in the development of CCU technologies. The effectiveness would depend on the actual CO\textsubscript{2} reduction that is being achieved with these technologies.
- The development of improved catalysts (lower heat demand, lower temperature required, avoiding rare and/or expensive materials) to make CO\textsubscript{2} useable as a feedstock for chemical purposes is regarded as one of the major challenges in this industry.
- Stakeholders notice that when the technology is evolving, collaborations become less common. High investments and protection of Intellectual Property make open communication and collaborations more complex.
- According to stakeholders, the focus in the development of CCU technologies is on individual technologies and there is a need for an integrated platform for CCU technologies. At this platform ideas and experiences can be exchanged and it might be a good breeding place for new ideas and identifying development and market opportunities. Recently, in the United
States of America a start was made to establish an association for CO\(_2\) reuse in North America. This association is in an early stage and is called “CO\(_2\) Asset Network”. The association aims to bring together utilities and other stakeholders interested in CCU.

The identified needs and barriers are used as input for the formulation of measures to stimulate the development of these technologies.
3 Opportunities for supporting CCU technologies

Innovation is regarded as a source of economic growth and employment. As such, to support innovations measures being taken include financial support for specific projects or research themes, support services for innovators (e.g. helpdesks, tools for business plans and innovation management), fostering interaction and cooperation among innovation players, and improve of innovation support (learning, sharing experiences, etc.) through regional programmes. The European Commission has therefore set several targets in the field of climate, energy security and industrial innovation. To achieve these targets, policies and regulations have been implemented to initiate action from stakeholders and to stimulate the development of technologies. In section 6 of Part 1 an overview of these measures is presented. In this section we look at existing EU instruments, policies and regulations to stimulate CCU technologies; do they already provide sufficient opportunities or is additional support required? What are opportunities to align those stimulation measures with existing policies and regulations? Finally, what are the positive or negative effects of the existing policy framework implemented on achieving the climate and energy security targets on the development of CCU technologies? A summary of the outcomes of the assessment are presented in an overview, indicating whether the effect is positive/contributing, mixed/indecisive or negative/imposing.

3.1 Push and pull policy instruments

The aim of technology stimulation is to stimulate the development from fundamental research towards commercial application. This can be done in many different ways, but they come down to two key strands of policies, namely technology push and technology (or market) pull policies.

Technology “push” policies refers to measures stimulating technological development by increasing efforts in research, demonstration and deployment (or “RD&D”). Key to successfully pushing technologies along the development pathway are making available venture capital and funding for research, development and demonstration (RD&D). In this context, an important measure is the EU Framework Programmes (FP7) and its successor Horizon 2020.

Policies can “pull” technology along the development cycle through the creation of measures that drive innovation on a commercial/financial basis (e.g. policies which create incentives for reducing environmental impacts of activities through the appropriate pricing of externalities). These measures are focusing on market-demand. Typical examples for technology pull are policies such as Eco labelling, Green Public Procurement (GPP), VAT differential schemes, feed-in tariffs and implementation of financial incentives to reduce CO₂ emissions, like EU-ETS. The main impact of pull instruments is creating a market for the products by influencing the buying behaviour of the customers. However, there are also impacts on the supply side, derived from change in a company’s expectations regarding the market prospects leading to change in innovative behaviour within the
company. This may lead to increased level of innovation within the companies affected directly by the demand-pull instruments; knock-on effects in diffusion of products to other markets (both geographical and sector-wise); and attracting manufacturers from other markets or sectors bringing in new technologies or innovative concepts.

Figure 5 shows a conceptual view on push and pull strategy.

![Figure 5 - Technology push versus market pull](image)

The main ‘push’ instruments at the direct disposal of the European Union include support for Research and innovation through the R&D Framework Programmes and the Competitiveness and Innovation Framework Programme. A high-level overview of the most important EU support measures for research and innovation is shown in table 14. The main ‘pull’ instrument is related to market interventions. In addition there are also the so-called command and control instruments like regulation and standard settings or banning products from the market.

It should be noted that using both push and pull policies at two different ends of a value chain poses the risk of creating market distortions, promoting perverse incentives, double counting emission reductions, and providing inappropriate levels of support. It will be critical that any policy mix developed appropriately reflects the benefits offered by the particular technology application, and avoids the potentially negative outcomes described above. It will also be important to consider how European policies designed to promote CO₂ reuse dovetail with international aspects of climate policy (e.g. through the United Nations Framework Convention and other multi-lateral initiatives such as the Clean Energy Ministerial technology group). This includes matters such as ensuring that CO₂ accounting methodologies used to determine benefits and allocate policy incentives are appropriately aligned with international standards (i.e. approaches developed by the Intergovernmental Panel on Climate Change; the IPCC).
Table 14 – EU support for innovation (European Commission, 2012b)

<table>
<thead>
<tr>
<th>Theme</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Financial support for innovators</td>
<td>The EU provides financial support for innovators mainly through three funding programmes:</td>
</tr>
<tr>
<td></td>
<td>• the Competitiveness and Innovation Framework Programme (CIP);</td>
</tr>
<tr>
<td></td>
<td>• the 7th Framework Programme for Research and Technological Development (2007 – 2013), and Horizon 2020 the new EU Framework Programme for Research and Innovation (2014 – 2020);</td>
</tr>
<tr>
<td></td>
<td>• the European Structural Funds’ operational programmes.</td>
</tr>
<tr>
<td></td>
<td>These programmes offer different types of funding (grants, loan guarantees, etc.) and can be used for different types of innovation related activities.</td>
</tr>
<tr>
<td>Support services for innovators</td>
<td>The Commission provides supporting services for innovators, both based on customised needs and generic internet tools.</td>
</tr>
<tr>
<td>Foster interaction and cooperation among innovation players</td>
<td>The intention of these measures is focused on establishing contacts and networks for sharing ideas, knowledge on the development of technologies. Eventually, this can result in collaborations.</td>
</tr>
<tr>
<td>Improve innovation support</td>
<td>These measures focus more on the stimulation of innovation in the general sense, by creating a framework that supports and facilitates innovation. Experience and mutual learning are used to support current innovation trajectories through national and regional innovation agencies and technology transfer offices. Examples are support of capacity building of innovation facilitators, such as investors and banks or provision of access to good practices and methodologies for innovation support.</td>
</tr>
</tbody>
</table>

3.2 EU support for innovation in CCU

In this section we will discuss instruments to support innovation which are relevant for the development, implementation and deployment of CCU technologies. We focus on Horizon 2020 and two instruments stimulating innovation as they are deemed most relevant for CCU technology development; technology prizes and Knowledge and Innovation Communities. In the last subsection we conclude on possible synergy of existing innovation support measures to address the listed needs and barriers in section 2.4.

3.2.1 Horizon 2020 – EU Framework Programme for Research and Innovation

The EU Framework Programme is one of the most extensive R&D stimulation programmes in Europe. The current Framework Programme (FP7) – active from 2007 to 2013 - is mainly directed towards research. Its main goal is to boost growth and employment in the EU in the context of a global economy. The Framework Programme matched the EU’s research policy to its ambitions in terms of economic and social policy by consolidating the European Research Area (ERA).

The successor of FP7 is Horizon 2020 and will be launched on January 1, 2014. Horizon 2020 will integrate various supporting initiatives of the EU. Horizon 2020 will bring together all existing Union research and innovation funding, including the Framework Programme for Research, the innovation related activities of the Competitiveness and Innovation Framework Programme, and the European
Institute of Innovation and Technology (EIT). The main differences between FP7 and Horizon 2020 are:

- bringing together of research and innovation in a single programme;
- focusing on multidisciplinary societal challenges which the European citizens face; and
- simplifying the participation of all companies, universities, and other institutes in all EU countries and beyond.

The total budget of Horizon 2020 will be over €1,000 billion of which €383 billion is earmarked for sustainable growth and natural resources. Although the detailed programme of Horizon 2020 is not yet established, there is information on the priorities and key challenges.

**Relevance of FP7 and Horizon2020 for CCU**

Under the current Framework Programme (FP7) CCU has not – unlike CCS - specifically been mentioned as one of the research areas. Nevertheless, several CCU technologies were funded in FP7, including research into renewable methanol, algae, mineralisation and polymers. Table 15 provides a non-exhaustive list of CCU projects.

<table>
<thead>
<tr>
<th>CCU topic</th>
<th>Aim of project</th>
<th>Acronym</th>
</tr>
</thead>
<tbody>
<tr>
<td>Renewable methanol</td>
<td>Exploiting a photo-electro-chemical (PEC) CO₂ conversion route for the synthesis of methanol as a key intermediate for the production of fine chemicals</td>
<td>ECO₂CO₂</td>
</tr>
<tr>
<td>Algae: renewable energy production through microalgae cultivation: Closing material cycles</td>
<td>Determine the feasibility of using sunlight transformation capacity of microalgae to enhance biogas production of anaerobic digestion processes, by means of CO₂ capture from biogas and co-digestion of waste and microalgal biomass.</td>
<td>ALGAENET</td>
</tr>
<tr>
<td>Algae</td>
<td>Develop an alternative and innovative system for the treatment of biowaste and use of GHG emissions to produce biofuels, using macroalgae as a catalyst, in a multidisciplinary approach.</td>
<td>BIOWALK4BIOFUELS</td>
</tr>
<tr>
<td>Mineralisation (Cement)</td>
<td>ECO-CEMENT will allow recovering valuable resources from industry, capturing CO₂ and transforming both products into ecological cement that can be used in construction or novel environmental applications.</td>
<td>ECO-CEMENT</td>
</tr>
<tr>
<td>Polymer</td>
<td>Develop the benchmarking criteria necessary for comparing various emerging CO₂ reuse technologies based on their potentials at large scales in light of economic, environmental, and technological factors.</td>
<td>B-COR</td>
</tr>
</tbody>
</table>

Under Horizon 2020 CCS will remain as a topic in the framework programme. The aim will be to enable the commercial deployment of CCS technologies for fossil fuel power plants and other carbon-intensive industries going into operation after 2020. Support will be given, in particular, to
demonstrate the full CCS chain for a representative portfolio of different capture, transport and storage technology options. This will be accompanied by innovative research to further develop more competitive capture technologies, improved components, integrated systems and processes safe geological storage and research to rational solutions for the large-scale re-use of captured CO₂.

One of the bottlenecks in CCU development and deployment is crossing the ‘Valley of Death’, i.e. providing the opportunities to translate knowledge via technology development and pilot/demo project into competitive manufactured products. Despite not being recognised (currently) as topic in Horizon 2020, CCU has several distinct features which seem better addressed in Horizon 2020 than in the current FP7. The main priorities of Horizon 2020 are:

- The integration of research and innovation by providing seamless and coherent funding from idea to market;
- More support for innovation and activities close to the market, leading to a direct economic stimulus;
- A strong focus on creating business opportunities out of our response to the major concerns common to people in Europe and beyond, i.e. ‘societal challenges’;

The stronger connection between RD&D and market creation on the one hand and addressing societal challenges like climate change at the other hand will make it easier to develop CCU technologies with promising economic and environmental potentials. In this respect, it is useful to acknowledge a new public private partnership SPIRE initiated by the process industry, where CCU technologies can be addressed (see box 5).

**Box 5 – SPIRE an example**

SPIRE (sustainable process industry through resource and energy efficiency) is a proposal from the private sector for a European Private Public Partnership (PPP) dedicated to innovation in resource and energy efficiency and enabled by the process industries to be launched as part of the Horizon2020 framework programme. Its ultimate goal is to promote the deployment of innovative technologies and solutions required to reach long term sustainability for Europe and its process industries in terms of global competitiveness, ecology and employment.”

A reduction in fossil energy intensity of up to 30% from current levels by 2030 through a combination of, for example, cogeneration-heat-power, process intensification, introduction of novel energy-saving processes, and progressive introduction of alternative (renewable) energy sources within the process cycle.

By 2030, up to 20% reduction in non-renewable, primary raw material intensity versus current levels, by increasing chemical and physical transformation yields and/or using secondary and renewable raw materials. A full life cycle cost analysis is required to consider all effects of using secondary and renewable feedstocks (e.g. water usage) and to prove the sustainability advantage.

Horizon 2020 is aiming to build leadership in enabling and industrial technologies, with dedicated support for ICT, nanotechnologies, advanced materials, biotechnology, advanced manufacturing and processing, and space, while also providing support for cross-cutting actions to capture the accumulated benefits from combining the aforementioned several Key Enabling Technologies. Figure 6 shows an example of the multiple key technologies essential for developing CCU technologies.
Horizon 2020 integrates research, industrial innovation and environmental issues. This will make it easier to draw attention to CCU technologies as they can potentially addressing multiple policy targets; e.g. various CCU projects can find its place where cross cutting themes are addressed.

Figure 6 – Relation CCU and key technologies (Klotz, 2012)

Horizon 2020 will focus resources on three distinct, yet mutually reinforcing, priorities, where there is clear EU added value: Excellent science, Industrial leadership and Societal challenges.

- Under the key area ‘Excellent science’ the topic Future and Emerging Technologies: Collaborative research to open new fields of innovation (budget of €3100 million) will provide opportunities to perform research and development in CCU technologies.
- Under ‘Societal challenges’, the topics Climate action, resource efficiency and raw Materials (budget €3160 million), and Secure, clean and efficient energy (budget €5782 million) are relevant for CCU. With the EU objective “to make the transition to a reliable, sustainable and competitive energy system, in the face of increasingly scarce resources, increasing energy needs and climate change” (Kougionas, 2012), several CCU technologies (e.g. renewable methanol, formic acid production) could be eligible under this key challenge.

As all three key areas will provide opportunities to include research and development in CCU technologies, there is a risk that projects addressing CCU topics will be spread over different areas, becoming less visible and lack opportunities for synergy. A possible way to improve this is to define CCU as a specific topic under future EU Framework Programme. This could stimulate and accelerate the development of CCU technologies considerably.
3.2.2 Technology prizes

A relatively new approach in EU research and innovation funding is awarding prizes for innovative ideas, concepts and technologies (instead of awarding proposals). Prizes are a way of bringing fresh ideas to problems which can seem intractable, as they are not prescriptive in terms of the approach to be taken. This form of funding has become popular worldwide thanks in part to private, non-profit organisations, which have delivered impressive proofs of concept of this new tool to spur innovation.

In the prize concept the financial reward does not go to the best proposals, but to the innovators who come up with the best working solutions. Prizes don't require complex control systems and mostly attract a higher quality results than traditional grant systems. Nevertheless prizes are not a panacea and there are some drawbacks. They tend to work where entry barriers are low and innovation is not capital-intensive. Prize competitions have to be properly promoted and designed. In addition, prizes tend to overlook basic research, which can lead to fundamental but unexpected results. Regulations on Intellectual Property have to be clear, and in some countries such as Italy there are administrative barriers to the organisation of prizes.

Prize competition can be an instrument to identify promising CCU technologies from a broad range of technologies being discussed in the literature or during workshops. The conditions for the Prize, however, need to be carefully designed and the innovator has to show that his innovation fulfils these criteria. Prizes can be awarded for innovative technologies that address multiple targets (e.g. emission reduction, environmental sound, EU relevant and competitive), i.e. it should be proven that there is sufficient demand for the product.

The use of prizes could help to discriminate between technologies with unproven claims in the field of climate and energy security targets on the one hand and competitiveness and employment at the other.

3.2.3 Knowledge and innovation communities

In Europe various communities and initiatives exist to support knowledge development and innovation. Climate-KIC is one of three Knowledge and Innovation Communities created in 2010 by the European Institute of Innovation and Technology (EIT). The aim of this institute is to accelerate and stimulate innovation in climate change mitigation and adaptation, by integrating a network of European partners from the private, public and academic sectors. Climate-KIC provides new solutions by education, innovation and entrepreneurship. Climate-KIC receives funding from academic and private sector partners, the European Commission and a grant from EIT. Climate-KIC addresses four themes to respond to the challenge of climate change: (1) Managing climate drivers; (2) Water management; (3) Low carbon cities; (4) Zero carbon production. The current focus does not include specifically CCU related innovations (the latter theme currently focus on bio-based solutions), and

---

14 A Prize-related initiative from the European Commission is the "World You Like Challenge". In this initiative the EC wants to stimulate creative and innovative minds from across the EU to put their low-carbon initiatives to the test and inspire others to follow suit. See: http://world-you-like.europa.eu/en/success-stories/about-the-contest
adaptation is required to cover the full potential of CCU technologies. Climate-KIC currently finances the B-COR project, a 1 year Pathfinder project (running until April 2013): “B-COR develops the benchmarking criteria necessary for comparing various emerging CO₂ reuse technologies based on their potentials at large scales in light of economic, environmental, and technological factors.” A key final output of the project will be recommendations for directions of future innovation projects including a survey of relevant SMEs and start-ups. Further information can be found at: http://www.climate-kic.org.

KIC-InnoEnergy is another Knowledge and Innovation Community. This European commercial organisation fosters the integration of education, technology, business and entrepreneurship and strengthens the culture of innovation. KIC-InnoEnergy addresses sustainable energy as its priority area. Reduction of energy costs and reducing greenhouse gas emissions are two of the main themes. Further information can be found at: http://www.kic-innoenergy.com.

Other initiatives to stimulate innovation and the development of low-carbon technologies are “The Innovation Union” (see Part 1, Section 6.3) and “A resource-efficient Europe”. Both of the initiatives are among seven flagship initiatives of the Europe 2020 Strategy for a smart, sustainable and inclusive economy.

- The goal of the Innovation Union is to make Europe a world-class science performer by removing obstacles to innovation (e.g. remove expensive patenting and slow standard setting) and improve collaborations between public and private sector (European Commission, 2012c). As mentioned in Part 1 of this report the Innovation Union includes industrial innovation as a key part of sustainable growth. CCU technologies could benefit from this initiative as it aims to stimulate private sector investments and to increase European venture capital investments.
- A resources-efficient Europe supports the shift towards a resource-efficient, low-carbon economy to achieve sustainable growth. The goal of the initiative is to create a framework for policies supporting the shift towards a resource-efficient and low-carbon economy by helping to build an integrated and strategic approach to ensure actions for 2020 and pave the way for more actions towards 2050 (European Commission, 2011d). CCU technologies could benefit from this initiative when proven to comprise low-carbon technologies.

### 3.2.4 CCU stimulation measures synchronised with existing innovation measures

For some of the suggested measures - mentioned in section 2.4 – stimulating is possible by synchronising existing innovation measures with the development needs of CCU technologies. In table 16, these measures are reflected including the possible synergies. From the table can be concluded that:

- There are possibilities for synchronisation with existing innovation stimulation measures to stimulate CCU technologies;
- There is no structural support for large-scale demonstration projects;
Some of the technologies cannot be synchronised under innovation measures and should be stimulated in other ways.

Table 16 – Synchronising existing European innovation measures to support CCU development

<table>
<thead>
<tr>
<th>Suggested support measure</th>
<th>Possible synergy with existing innovation support measure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Improve CCU R&amp;D effort</td>
<td>Horizon 2020 will be an important R&amp;D and innovation stimulation measures. Under the current and previous Framework Programmes, CCU was not included as a specific topic. Possibly CCU could be a topic under Horizon 2020. CCU technologies could potentially benefit from Innovation Union by streamlining technology development, by removing implementation obstacles, and by stimulating funding from private sector.</td>
</tr>
<tr>
<td>Dedicated (financial) support for large-scale demonstration projects</td>
<td>Not supported under existing innovation support measures</td>
</tr>
<tr>
<td>Stronger financial incentives to stimulate the development of CCU technologies</td>
<td>&quot;A resources-efficient Europe&quot; is aiming for a policy framework that is supporting the shift towards low-carbon technologies.</td>
</tr>
<tr>
<td>Assess possibilities to simplify authorisation process, e.g. for new algae species or other types of cement</td>
<td>Not supported under existing innovation support measures</td>
</tr>
<tr>
<td>Create awareness, visibility and acceptance for CCU technologies and CCU products</td>
<td>Projects under IEE to promote the CO₂ reuse alternatives and create awareness. These projects will typically take place in a later stage, when technologies near commercialisation. Project could take place under ALTENER (alternatives for energy storage) and STEER (CO₂ reuse for alternative fuels)</td>
</tr>
<tr>
<td>Develop, agree and approve on a methodology to calculate the net greenhouse gas emission reduction from (CCU) technologies</td>
<td>Not supported under existing innovation support measures</td>
</tr>
<tr>
<td>Establish an association or platform for meetings and exchange of knowledge and ideas in the field of CCU.</td>
<td>Not supported under existing innovation support measures</td>
</tr>
</tbody>
</table>

a) As mentioned in Section 6.1.2 of Part 1, there are programmes to support demonstration projects, such as NER300 and EEPR. These schemes were specifically introduced to create long-term economic support for CCS-projects and for renewable projects.

3.3 Implications of the stimulation of CCU technologies on European Policy framework

The development and deployment of CCU technologies may contribute to reaching EU policy objectives notably in the field of climate action (e.g. CO₂ reduction targets) and energy security (e.g. transition towards renewable energy). Existing EU policies and measures addressing aforementioned policy areas may already have implications on CCU technology development. In some cases this will be positive, stimulating the development. In other cases it may (unforeseen) create barriers. Key barriers in realising the potential of CCU include economics and regulatory issues:
• **Economic** – the costs of capturing, purifying, transporting and utilising CO₂ is apparently not economically attractive at the current time in comparison to other uses of capital or alternative means of supplying the same goods or service.

• **Regulatory** – several challenges exist in the EU to realise wider uptake of CCU technologies. These include issues around recognition of CCU applications as CO₂ abatement techniques – and inclusion within carbon pricing schemes such as EU ETS – and the acceptance of products derived from CO₂ utilising processes in the relevant end markets.

Typically, where technologies offer promising solutions to politically desirable outcomes, but face economic and regulatory challenges to their realisation, there is a need for market intervention through policy. The following section considers – in broad terms – the potential policy tools that may be used to enhance the attractiveness of CCU technologies within Europe.

In Europe, one of the key market interventions needed to support abatement of CO₂ emissions is already in place, namely the EU Emissions Trading Scheme. However, as has been seen in Europe over recent years – even where additional financing mechanism have been put in place – CCS projects have struggled to get off the ground. Therefore, similar economic challenges can be expected in delivering captured CO₂ for CCU applications. Conversely, CCU technologies can offer means to at least partially offset some of the costs of capturing CO₂, and therefore can partially help support CCS deployment. For this reason, CCU technologies are increasingly attractive in a European policy context, and the analysis presented in this paper is a timely addition to policy considerations around CCS in the EU.

In Section 6 of Part 1, the potential contribution of CCU technologies on achieving targets set by the Commission on climate action and energy security are described. In this section the implications of the selected CCU technologies on achieving these targets is being assessed. First the implications on climate action and energy security are being described in two subsections. In the third subsection an overview of the implications is presented in a table.

### 3.3.1 Implications on existing policies

A main focus for climate action policies is the reduction of CO₂ emissions in the EU. In Section 0 of Part 1 potential abatement effects of the various CCU categories are indicated. The contribution to abatement is implicated by important factors like permanence of storage (permanent, semi-permanent, short cycle), possible leakage, and the overall efficiency improvement. To what extent the various CCU technologies (potentially) may contribute to emission reduction is not yet determined, at least for most technologies and in large detail. This is mainly due to the fact that there is no developed, accepted and approved methodology to determine the contribution of each technology to emission reduction.

Below examples are described of how existing policies can influence the development of CCU technologies:
EU ETS Monitoring and Reporting Guideline (MRG) requirements – it will be important that CO₂ captured and exported for the purpose of CCU is appropriately recognised for capturing entities, although striking the appropriate balance in this context will be challenging. As highlighted in Figure 4, some CCU technology pathways lead only to temporary abatement of CO₂, or lead to abatement of CO₂ through substitution effects in other sectors of the economy. Presently, whilst geological storage of CO₂ may be recognised as not emitted under international GHG inventory accounting rules (i.e. the 2006 IPCC Guidelines for National Greenhouse Gas Inventories), technologies which deliver temporary storage of CO₂ are not. Since the EU ETS is a regional scheme, it is conceivably possible to take a different approach and provide recognition of the temporary storage techniques as abatement measure within the scheme, but the EU would not be able to claim these emission reduction benefits at the international level.

The revised MRG Regulation for Phase III specifically restricts the scope of which types of transfers of CO₂ outside of a qualifying installation can be deducted from its GHG inventory; as it stands under the new Regulation, only transfers of CO₂ either to another ETS installation or for injection and geological storage may be deducted. This has been done to "close loopholes" in the old MRG Decision (see recital 13 of the preamble). As a result, transfers of CO₂ for other purposes may not be subtracted from the installations GHG inventory. Implicitly this means that CCU technologies cannot be recognised in the EU ETS Phase III. Nevertheless, there is scope for changes in this requirement as acknowledged in the preamble recital 13 where it is suggested that this development should not “…exclude future innovations”. We take this to mean that it is probably possible to opt-in of new activities/technologies involving things such as CCU under Art. 24 of the ETS Directive, subject to the submission of appropriate MRGs – this would take place through a comitology process under Art. 23 of the ETS Directive. This is a sensible policy given the uncertainty regarding the permanence of abatement achieved through some CCU applications, as highlighted in our illustrative in the text and our Sankey Diagram (Figure 4). Clearly, further consideration of this approach will be necessary if CCU technologies are to be offered a carbon price signal in the EU going forward. Further analysis on the various pathways for CO₂ emission avoidance – as per Figure 4 – will likely be necessary before progress can be made.

Some CCU technologies have a strong link with renewable energy. In algae cultivation, polymer processing, formic acid production and renewable methanol, renewable energy is used to power the processes. Renewable methanol and formic acid can for instance be used as medium for peak shaving and energy storage, which can stimulate the transition towards renewable energy and enhance EU’s security in energy supply. Other technologies like the utilisation of CO₂ in enhanced oil recovery or enhanced coal bed methane recovery can improve the domestic fossil fuel production while simultaneously storing CO₂. In some cases, existing policies implemented to stimulate the

16 Previous MRGs allowed any CO₂ transferred out of a qualifying installation to be subtracted from the installations inventory, thus offering a carbon price incentive for CCU.
Implementation of renewable energy can impose the development of CCU technologies. Below the relevance of the RED and FQD for CCU are discussed.

**Renewable Energy Directive (RED)** – the RED sets for each Member States a target for the share of renewable energy sources in its gross final consumption in 2020. The main focus of RED is on implementation of biofuels and renewable electricity. At the time the RED was adopted, the CCU technology to produce renewable methanol was not available. For transportation fuels, the focus was on biofuels. The result is that most Member States have set their targets specifically for biofuels, most likely sufficient to achieve their renewable targets. This reduces their willingness to implement regulations to stimulate implementation of non-bio alternatives, like renewable methanol. At the moment, there seems no significant role for renewable methanol in the EU.

In principle methanol is qualified under RED when it is produced with energy from renewable sources. According to stakeholders, the interpretation of the Directive by the Commission is that the methanol should be produced with certified 100% renewable energy. This implies that producing methanol with power obtained from a grid, transporting electricity both from renewable and non-renewable energy sources, does not qualify. Also the use of certificates (guarantees of origin) is currently not allowed under the RED. This requirement forms a potential barrier for large-scale introduction of renewable methanol from non-biomass sources. The disconnection of the physical supply from the administrative supply of the renewable power will already provide better opportunities for renewable methanol production as it allows integration of the production plant with the power grid. This allows for better peak shaving – and lower prices - of the energy supply system.

In October 2012, an amendment to the RED was published to address indirect land-use change emissions for biofuels (European Commission, 2012d). This amendment does not address the aforementioned barrier.

**Fuel Quality Directive (FQD)** – presently the latest version of the Fuel Quality Directive allows conventional petroleum products to be blended with methanol at a rate of 3% by volumetric concentration. According to renewable methanol producers, it is technically possible to blend up to 10%. Whilst this is a potential restriction on the rate of renewable methanol supply, current consumption of petroleum by motor vehicles in Europe is excess of 8 billion litres, which would place a cap at about 250 million litres of methanol just for motor vehicles. Presently, the ambitious plans of Europe’s largest producer of renewable methanol in Europe (CRI) amount to 50 million litres per year (see Box 3), so this unlikely to be a barrier to renewable methanol production in the near-term. For algae-derived biofuels, it is also unlikely that regulatory controls on blending rates will present a serious near-term barrier to their further development, although further analysis of the supply and cap may be warranted.

One of the amendments in the FQD, “Vapour pressure of petrol” facilitates the blending of ethanol up to 10% of the total content. Instead of ethanol, methanol can be used, obtaining the same result. However, at the moment the FQD amendment was adopted, renewable methanol was basically non-existing. Therefore, only ethanol was acknowledged under this amendment, meaning that there is no waiver for using methanol.
**Cement blending rates** – within the EU, European Standard EN197-1 sets limits on the rates at which various products may be blended for different types of cements. It has not been possible to undertake detailed analysis on whether this could have any effects on the amounts of products fabricated through CO₂ mineralisation that could be sold into the European construction industry. A further understanding of the classification of the types of products that could be produced through CO₂ mineralisation, and which items they could substitute in cement manufacture will be needed before a clear idea on the potential barriers is possible.

### 3.4 Overview of implications of existing policies on the development of CCU technologies

In this section an overview is presented of the possible implications of existing policies on the development and deployment of the selected CCU technologies, and how these technologies could contribute to policy objectives on climate and energy security. Referring to section 6 of Part 1, important elements in achieving the policy objectives are:

- Avoiding CO₂ emissions by storing the CO₂ (permanent or semi-permanent);
- Reducing energy consumption by using CCU technology;
- CCU technologies can stimulate the development of CCS technologies;
- Use of renewable energy to power CCU technologies and storing overproduction of renewable energy;
- CCU technologies can be used to produce biofuels;
- Closing the carbon cycle and decreasing the pressure on the use of fossil resources.

As described in the previous section, CCU technologies can have an effect on climate action and EU’s energy security and the other way around can the existing policy framework have implications on the development of CCU technologies.

In Table 17 the outcome of this assessment for the selected CCU technologies is presented. The table summarises the findings from this section completed with information obtained from experts (interviews, workshops), observations made in Part 1, etc. In addition the implications are presented qualitatively: contributing (green colour), imposing (red colour) or no significant effect (white). In some cases the effect could not be determined and it therefore qualified as an indecisive effect (amber colour). The qualifications are further clarified in the legend below the table.
### Table 17 – Implications of stimulation of CCU technologies

<table>
<thead>
<tr>
<th>Technology</th>
<th>Energy security</th>
<th>Climate</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Renewable methanol</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>production</strong></td>
<td><strong>Effect of CCU technology on achieving targets</strong></td>
<td><strong>Effective use renewable energy</strong></td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>Potential for renewable energy storage</strong></td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>Contributing to blending target for transportation fuels</strong></td>
</tr>
<tr>
<td></td>
<td><strong>Effect of directives on stimulating the development of CCU technology</strong></td>
<td><strong>CO₂ storage is temporary</strong></td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>Improved GHG balance compared to biofuels</strong></td>
</tr>
<tr>
<td><strong>Formic acid production</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Effect of CCU technology on achieving targets</strong></td>
<td>Effective use renewable energy</td>
<td>CO₂ storage is temporary</td>
</tr>
<tr>
<td></td>
<td>Potential for renewable energy storage</td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>Effect of directives on stimulating the development of CCU technology</strong></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Potential for renewable methanol is limited by biofuel focus and blending limit</td>
<td></td>
</tr>
<tr>
<td><strong>Algae cultivation</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Effect of CCU technology on achieving targets</strong></td>
<td>Potential of algae is large</td>
<td>Potential of algae is large</td>
</tr>
<tr>
<td></td>
<td>Algae for biofuels is regarded as renewable under existing policies</td>
<td>Reduces indirect land use changes</td>
</tr>
<tr>
<td></td>
<td><strong>Effect of directives on stimulating the development of CCU technology</strong></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Algae for biofuels is regarded as renewable under existing policies</td>
<td></td>
</tr>
<tr>
<td><strong>Carbonate mineralisation</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Cement</strong></td>
<td><strong>Effect of CCU technology on achieving targets</strong></td>
<td><strong>Substantial CO₂ emission reduction potential</strong></td>
</tr>
<tr>
<td><em>Fixed CO₂ not eligible under EU ETS</em></td>
<td><strong>Effect of directives on stimulating the development of CCU technology</strong></td>
<td>Fixed CO₂ not eligible under EU ETS</td>
</tr>
<tr>
<td><strong>Other</strong></td>
<td><strong>Effect of CCU technology on achieving targets</strong></td>
<td><strong>Substantial CO₂ emission reduction potential</strong></td>
</tr>
<tr>
<td><em>Fixed CO₂ not eligible under EU ETS</em></td>
<td><strong>Effect of directives on stimulating the development of CCU technology</strong></td>
<td>Fixed CO₂ not eligible under EU ETS</td>
</tr>
<tr>
<td><strong>Polymer production</strong></td>
<td><strong>Effect of CCU technology on achieving targets</strong></td>
<td><strong>CO₂ abatement (permanence) depending on product</strong></td>
</tr>
<tr>
<td></td>
<td>Closing carbon cycle</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Reduce dependency on fossil-based raw materials</td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>Effect of directives on stimulating the development of CCU technology</strong></td>
<td></td>
</tr>
<tr>
<td></td>
<td>*<em>Not relevant</em></td>
<td></td>
</tr>
</tbody>
</table>

**Legend:**
- **Contributing**
- **Indecisive**
- **imposing**
- **No sign. effect**
a. When the CO₂ is generated specifically for the production of the methanol, the carbon effect may be negative. Example is the extraction of CO₂ from geothermal reservoirs, which would otherwise not have been released to the atmosphere. In case CO₂ is used from flue gases or atmospheric CO₂, the effect is neutral, unless the renewable energy would not have been used otherwise.

b. Biofuels should reduce at least 35% of the GHG emissions compared to its reference, increasing to 60% reduction in 2014. For non-biomass-based fuels the required emission abatement is 100%.

c. The focus of Member States is primarily on implementation of biofuels limiting in practise application of alternatives.

d. The current blending limit is set to 3%. In practise this does not pose a limiting factor to its application in the near future.

e. Not relevant indicates that the implemented regulations do not affect the development or deployment of the CCU technology

f. Whether it can obtain a significant market share is highly uncertain.

g. A desire for energy security (specifically, transport fuel) and high volume CO₂ abatement are key drivers in the push for algal oil.

h. Not relevant indicates that the CCU technology does not contribute to the policy objective.

i. CO₂ emissions are reduced by avoiding process emissions and (permanent) fixation of carbon in the cement product.

j. CO₂ emissions are reduced by (permanent) fixation of carbon in mineral products.
4 Building a long-term strategy for CCU in the European Union

In this study we looked at the potential role of CCU technologies in contributing towards European policy objectives, in particular energy security and climate action goals. In addition consideration was given to the implications of existing policies on the development and deployment of CCU technologies in terms of e.g. potential barriers or impediments to their deployment.

The term CCU technology is an "umbrella" term covering many different technologies in different states of development and deployment. Therefore, for pragmatic reason, a more detailed assessment was made of six technologies that are considered to be the most promising types of CCU technologies for Europe. The selection of the technologies was based on various criteria including economic and CO₂ abatement potential, relevance for the European Union and environmental health and safety (EHS) aspects.

A large share of the CCU technologies are still in a very early stage of development with only limited activities at the research and demonstration scale, being pioneered by academia, research institutes and entrepreneurs. Others are already being developed at commercial scale e.g. renewable methanol production and the use of carbon dioxide to enhance oil recovery. This evolution is, however, generally restricted to certain niche circumstances favouring their development.

The various technologies have the potential to contribute to different and sometimes multiple EU policy targets, of which the most relevant are related to climate, energy security, and industrial innovation. However, whether and how much a CCU technology (potentially) contributes to one or more policy targets - e.g. reducing net CO₂ emission - is often unclear and not easy to determine, especially given an apparent paucity of data on performance of the various technologies, their costs, and challenges in developing comparable assessment methods e.g. LCA-based methodologies to address climate impact.

For the majority of the CCU technologies reviewed, there is still a wide gap between their current levels of research and the steps needed to progress to deployment in commercial markets. For this reason many still require support in various forms, in particular research funding. One of the challenges for CCU technologies is lowering their production costs. For some technologies such as algae production, which have the potential to produce a range of products, increasing emphasis on high value goods - such as nutraceuticals - rather than lower value products - such as petroleum - could help to promote commercial scale developments. In terms of policy development, for most of the technologies, push instruments – stimulating research and development for specific technologies - is likely to be the main focus for government support at the current time. An important next step would be the development of large-scale demonstration projects. This requires active involvement of...
the private sector willing to pioneer and invest in the development of the technology. For some CCU technologies the prospects are rather good as demonstrations are already on-going or being prepared (e.g. renewable methanol, polymers and some algae applications). For a few technologies, adaptation or refining existing policies and regulations may be necessary to facilitate the positive associated effects of the technologies and improve its competitiveness in the market. For example:

- Renewable methanol (not based on biomass) can be eligible under the Renewable Energy Directive only when the energy is fully obtained from renewable energy sources. Interpretation of the Directive resulted that grid-connected installations could not qualify when non-renewables were part of the grid. In practise this could hamper the uptake of this technology.
- CO\(_2\) utilisation is limited under the ETS because the revised MRG Regulation for Phase III specifically restricts the scope of which types of transfers of CO\(_2\) outside of a qualifying installation can be deducted from its GHG inventory; only transfers of CO\(_2\) either to another ETS installation or for injection and geological storage may be deducted. As a result, transfers of CO\(_2\) for other purposes may not be subtracted from the installations GHG inventory.

The CCU field is heterogeneous and communication between the various actors is limited - the nature of the technologies, the sectors involved, and the diversity of product markets makes this hardly surprising. In general terms, there is no common language and views amongst actors, which is to be expected given their diversity. Only recently, cross-cutting "CCU-driven" workshops and network of stakeholders are bringing together a wide range of actors involved in CCU, and broader areas of common interest - in particular policy is receiving greater attention on a common platform. As part of this project, the European Commission initiated in October 2012 a workshop open for all CCU stakeholders to discuss policy relevant aspects related to CCU. The workshop was well-attended, and appreciated by both the European Commission and the participants. However, it was apparent that there is probably still some way to go until a common set of views and language might be expected amongst actors in the CCU space.

Based on the findings in this report the following recommendations are drawn:

- To develop assessment methods to determine the impact of CCU technologies on reaching EU policy objectives. For climate goals this could be the development of LCA-like methodologies to objectively and independently evaluate the contribution of (promising) CCU technologies on reducing greenhouse gas emissions and thus contributing to climate policies.
- Unlike CCS, CCU is based upon the creation of products or services. It faces a range of barriers specific to the market for those goods, notably its ability to compete commercially with incumbent products and processes. Existing policies such as the EU-ETS and RED should be considered and possibly adapted to make explicitly clear its applicability for such technologies. It should be noted that policies supporting CCU must be designed carefully depending on its contribution to CO\(_2\) emission reductions (see previous recommendation). It may be difficult to justify the provision of carbon price incentives to CCU technologies which contribution to emission reduction is disputable or when it only offer short-term storage of CO\(_2\) rather than long-term.
CCU technologies are spread over a wide variety of topics and sectors. For specific technological development activities it is, however, more effective to collaborate or share knowledge with others having a mutual understanding of the topic. To prevent that CCU will only exist as a holistic group of technologies a basis for CCU should be created to increase the visibility of CCU. In this way the interest of CCU technologies can be better articulated and expressed, which could stimulate better coordination for CCU research within Europe; perhaps with cross-cutting research initiatives being promoted. This can be done by organising regular "CCU-driven" meetings, or when deemed necessary, by establishing a dedicated CCU (technology) platform where stakeholders can share ideas, problems and knowledge. The outcomes of such meetings could be used to better inform the policy-makers regarding e.g. the status of CCU technology development in Europe, policy and research needs, and developments occurring in parts of the world outside of Europe. It may also provide the European Commission an excellent platform for communicating their vision on CCU and its role in energy and climate policies. The European Commission could initiate, facilitate or support such annual meetings, workshops or roundtables.

Consider the options for including a CCU technologies-specific thematic programme under EU research, as is currently done for CCS. Qualifying CCU technologies as a separate area for research may improve the visibility of the technologies and create the opportunity for dedicated calls, as CO₂ reuse technologies have many linkages in addressing EU policies. There are possibilities to frame them under the various policy topics (energy, climate, innovation, industry). Given its multiple benefits CCU could or should also be addressed in cross-cutting themes under the framework programmes, starting with the EU framework programme Horizon 2020. Next to subsidies for proposals, Technology Prizes can stimulate the innovation in the area of CCU technologies. Such instrument is most appropriate for a diverse group of technologies addressing multiple policy targets as it allows for selecting the best technology based on pre-set criteria; it may reduce the uncertainty about the range of technologies, their costs and performance.

Explore opportunities to close the gap between research and commercial development. A possible way to do this could be through the promotion of public-private partnerships as an instrument to finance long lasting, higher risk projects.

Improve communication by the European Commission to the stakeholders in the field of CCU (e.g. maintaining dedicated website) and internally within the Commission to align CCU related activities and cross-cutting issues.¹⁷

The outcomes of this report will support the Commission in understanding how CCU technologies could contribute to achieving energy and climate action targets bringing them in the position to draw conclusions on the potential impact of CCU technologies on addressing the mentioned policy targets including EU’s competitiveness, which technologies should be pursued. As we expect long lead times before large-scale implementation of CCU technologies will be possible, such innovation cycles should probably be repeated also on the mid-term (after 2020).

¹⁷ Annex D presents two communication activities undertaken in this project; establishment of dedicated website (www.CO₂reuse.eu) and stakeholder workshop to discuss policy implications for CCU technologies.
Bibliography

Abengoa, 2012, Abengoa Bioenergia – corporate website, available at:

Abo Akademi, 2011, Mineralisation – it is now or never, url:

AlgaeCluster, 2012, European Commission demonstration project, available at:
http://www.algaecluster.eu/About/. Last viewed: December 27, 2012;

Bayer, 2010, Sustainable with CO₂RECT, available at:

Bayer, 2012, From climate sinner to useful material, available at:

BMBF, 2012, Germany’s research funding programme on CO₂ utilization, Presentation from Lothar Mennicken during CO₂ reuse workshop organised at October 24, 2012. Available at:


DNV, 2011, Carbon Dioxide Utilization: Electrochemical Conversion of CO₂ – Opportunities and Challenges;


European Commission, 2011a, COM 808: Communication from the Commission to the European Parliament, the Council, and the European Economic and Social Committee and the Committee of the Regions: Horizon 2020 - The Framework Programme for Research and Innovation;
European Commission, 2011b, COM 112: Communication from the Commission to the European Parliament, the Council, and the European Economic and Social Committee and the Committee of the Regions: A Roadmap to 2050 for moving to competitive low carbon economy;

European Commission, 2011c, COM 885: Communication from the Commission to the European Parliament, the Council, and the European Economic and Social Committee and the Committee of the Regions: Energy Roadmap 2050;


European Commission, 2012b, Industrial innovation – Overview of EU support for innovation:


European Union, 2011b, "Background on Innovation in Europe, 2011". Based on EUROSTAT and OECD data.


Holcim, 2012, ACC India: Industrial farming of CO₂ into algal biomass fuel. Available at:


IPPR (Institute for Public Policy Research), 2012, Growing pains: British industry and the low-carbon transition;


Li Jia, 2011, China Australia geological storage of CO₂ (CAGS) presentation August, 2011. Available at www.cagsinfo.net;

Low Carbon Futures, 2011, Carbon Capture and Utilisation in the green economy;


Methanol Institute, 2012, Available at: www.methanol.org. Last viewed: July 20, 2012;


North, M. "Technical aspects of CO₂ reuse" Presentation to CO₂ reuse stakeholder workshop, Brussels, 24 October 2012. Available at: www.CO₂reuse.eu;


NETL, 2011b, Utilization of CO₂ in High Performance Building and Infrastructure Products. US DOE/NELT fact sheet;

NETL, 2011c, Integrated Electrochemical Processes for CO₂ Capture and Conversion to Commodity Chemicals. US DOE/NELT fact sheet;


Science Daily, 2008, url: http://www.sciencedaily.com/releases/2008/05/080507105630.htm;


USA Today, 2010, U.S. funds efforts to turn CO₂ emissions into products. Available at: http://content.usatoday.com/communities/greenhouse/post/2010/07/doe-funds-CO2-efforts-/1#.UMixfyj4LTo;


Zevenhoven, 2009, Inorganic CO₂ utilisation and mineralisation, BMBF CCU seminar 2009;


Annexes
Annex A – Interviews and survey questions

In this Annex, the various parts of interviews have been included:
- The interview questionnaire
- Online questionnaire, spread among the participants of the CO₂ reuse workshop

Interview questionnaire

Knowledge development

Knowledge development include activities related to early phase technological developments such as R&D and pilot-scale tests

1. In what development phase is [CCU technology] in Europe? Lab-scale, pilot-scale, applied, etc.?
2. Are you satisfied with the current status of knowledge development on [CCU technology]? What are you missing?
3. How would you rate the knowledge development (regarding variety, quality, etc.) on [CCU technology] in Europe on a scale from 1-5, 5 being very good?
4. If it is not a 5, what is needed to rate it a 5?
5. How can policies and regulation stimulate the development of knowledge development for this technology?

Entrepreneurial activities

Demonstration projects and advanced development to prepare the technology for commercial introduction are typical activities that are included in this function. Mostly, these activities are performed in corporate companies, hence the term entrepreneurial activities.

6. What is the current status of entrepreneurial activities on [CCU technology] in Europe? Pilot-scale, large-scale, commercial-scale, fully integrated, etc.?
7. Are you satisfied with the current status of these activities? What are you missing?
8. How would you rate your satisfaction on the current demonstration projects and other entrepreneurial activities on [CCU technology] in Europe on a scale from 1-5, 5 being very good?
9. If it is not a 5, what is needed to rate it a 5?
10. How can policies and regulations stimulate the development of entrepreneurial activities for this technology?

Knowledge diffusion

Besides development within companies and research laboratories is collaboration and knowledge exchange an important driver for technological development. Knowledge diffusion includes activities such as collaboration (on knowledge development, demonstration projects, etc.), but also conferences and workshops.
11. How common is collaboration between stakeholders in the development of [CCU technology]? How important is this in the development of this technology?
12. How would you rate the knowledge diffusion (regarding collaboration, networking, etc.) on [CCU technology] in Europe on a scale from 1-5, 5 being very good?
13. If it is not a 5, what is needed to rate it a 5?
14. How can policies and regulations stimulate the development of knowledge diffusion for this technology?

**Market creation**

*New technologies often have difficulties competing in the market. However, they may bear advantages in niche markets, or be stimulated by specific market instruments*

15. When do you expect that [CCU technology] as a production technology will become commercially available? What is needed to create a market for these products?
16. What is the market potential for applications of [CCU technology]? What is the advantage of this technology over incumbent technologies?
17. Are there any instruments (e.g. environmental standards, EU-ETS, carbon tax, subsidies, etc.) in place to stimulate the market development of [CCU technology]?
18. To what degree are you satisfied with the current developments of a market for [CCU technology] on a scale from 1-5, 5 being very good?
19. If it is not a 5, what is needed to rate it a 5?
20. If not already answered in question 16: how can policies and regulations stimulate market creation for this technology?

**Resource mobilisation**

*Sufficient resources are essential for the development of new technologies, like CCU technologies.*

21. Are there national or European supported funding programmes for CCU technologies and [CCU technology] specifically?
22. To what degree are you satisfied with the current availability of resources for [CCU technology] (e.g. funding, human resources, etc.) on a scale from 1-5, 5 being very good?
23. If it is not a 5, what is needed to rate it a 5?
24. How can policies and regulations stimulate the availability of resource mobilisation for this technology?

**Creation of legitimacy**

*The acceptance of CCU technologies by a variety of (public) stakeholders, as well as the general public is important for the deployment of this technology.*

25. Do you experience any kind of public opposition against [CCU products] produced with this technology? Do you think that this is of any influence?
26. Can you rate the level of creation of legitimacy of [CCU technology] in Europe on a scale from 1-5, 5 being very good?
27. If it is not a 5, what is needed to rate it a 5?
28. How can policies and regulations stimulate creation of legitimacy for this technology?
**Guidance**

*Visions and expectations are important drivers for the development of CCU technologies. Guidance refers to judgement from public figures (e.g. scientists, politicians and environmentalists) that can (both positively and negatively) influence the eagerness of investors in CCU technologies.*

29. How large is the contribution of CCU technologies to CO₂ emission reductions? How large is the role of [CCU technology]?  
30. Are you experiencing any support from politicians, experts, etc. in the development of [CCU technology]? Would this be helpful?  
31. How would you rate the degree of guidance / demand articulation by governments or industry on a scale from 1-5, 5 being very good?  
32. If it is not a 5, what is needed to rate it a 5?  
33. How can policies and regulations stimulate guidance / attention for this technology?

**Online questionnaire**

After the CO₂ reuse workshop, participants were invited to fill out a questionnaire in which they could provide the project team with suggestions for improvements. The online questionnaire can be found at the CO₂ reuse website: [http://www.CO₂reuse.eu/form/14-questionnaire.html?lang=en](http://www.CO₂reuse.eu/form/14-questionnaire.html?lang=en)

The questionnaire included the following questions:

- What is your involvement in CCU (e.g. Fundamental academic research, industrial research, demonstration, market creation, …)?  
- Are CCU technologies sufficiently acknowledged by European funding programmes? If not, how can that be improved?  
- What barriers do you identify in the development of CCU technologies? (e.g. in the CCU area that you are involved in)  
- What actions are needed to overcome these barriers?  
- How can policies and regulations stimulate the development of CCU technologies?  
- What EU policies or regulation form barriers to implementation of CCU technologies (and why)  
- On what areas or activities should the European Commission focus in supporting and stimulating the development of CCU technologies?
Annex B – Selection criteria CCU technologies

Uptake potential

The uptake potential of a particular CCU technology/option provides an indication of the scale of its potential application (e.g. tonnes of CO₂ which could be utilised). This is clearly an important criterion both for policy-makers choosing where best to allocate resources and R&D support, but also for businesses considering the most promising emerging market opportunities and assessing their investment priorities. Those CCU applications with potential for transformative or step-change impacts, for example upon patterns of energy transformation and use, demand greater attention in terms of structured R&D and innovation support needs over the short and medium term than others with more limited, or niche, (albeit potentially beneficial) applications.

Several factors will together determine the uptake potential for CCU, including market demand, ability for product or service substitution, technical maturity and CO₂ utilisation rate. A first-pass assessment of these issues for the technologies under study has been outlined in Part 1 (in particular Section 1 and 1, and Table 6), and issues such as the potential size of the demand for the good or service being provided, expected demand export capacity, product alternatives, barriers to uptake and rates of CO₂ use are all discussed. This has provided the basis for the assessment described.

Economic potential

The uptake potential provides an indication of the potential scale which is technically possible for CCU to penetrate existing and new applications. However, whenever there is any degree of market competition for products and services, the costs and benefits of the new (CCU) technology compared to their alternatives will determine its economic potential, and therefore its ultimate uptake potential. Economic potential is an important factor when considering competing claims for R&D support or the development of policy incentives. Similarly, business will only invest in, and develop new technologies where there is a reasonable case for recovery of costs at a future time. Many of these factors for the technologies under study have been discussed in Part 1, Section 5.4, and include:

- Potential for commercialisation (i.e. whether the technology could ultimately be commercially viable without ongoing R&D or funding support)
- Input and end-use costs (e.g. input costs and whether they are comparable to competing goods/services)
- Process efficiency (e.g. whether the CCU application offers the potential for improved or optimised process efficiency)
- Macro-economic factors (e.g. whether there are wider considerations and effects that could increase the economic attractiveness of CCU applications such as future peak oil, interrupted energy supplies, decreasing availability of raw materials)
Applicability to the EU

As outlined in Part 1, CCU technologies are being developed and demonstrated at various locations worldwide, often as a result of regional or national circumstances and/or strategic priorities. A wide range of factors will determine the suitability of specific CCU technologies or applications to the EU. These include alignment with EU policy and regulation (e.g. policies relating to transport, fuels quality, biofuels and environmental protection, and whether there is potential for an enabling policy and/or regulatory framework to be developed as a precondition for CCU technology development); EU demand and market characteristics (e.g. how applicable is the technology to EU markets); value added potential (e.g. is there value added potential for EU industry compared to other regions developing CCU); export potential (e.g. is there a significant market export opportunity for EU goods and services in the sector); and geographical factors (see Part 1, Section 0).

Potential for GHG abatement

The EU GHG emission reduction policy commitments out to 2050, and the potential role that CCU technologies could play, are highlighted in Part 1, Section 6.1. The analysis outlined suggested that CCU technologies could play a role, although definitive views on the overall potential are difficult to gauge because the claims made for CCU technology regarding its potential to reduce GHG emissions are challenging to verify and are fraught with uncertainties; for some technologies the ability to result in a net emissions reduction may be highly dependent upon highly specific circumstances; for others, any such claims remain largely theoretical until key research breakthroughs can be made (most notably involving improvements in conversion efficiency).

Key factors which need to be considered in determining the ability of CCU to achieve GHG abatement include: permanence (in terms of whether emission abatement is short-lived or long-term); life cycle impacts (e.g. whether application reduces emissions across the life-cycle of production, consumption and end use for a particular or emissions are increased elsewhere in the value chain);18 absolute emission reductions (e.g. how much impact could the technology make against overall GHG emission reduction targets, in both the short and long-term); and support for CCS (whether it act as a catalyst for uptake of carbon capture and geological storage). Estimates in these contexts have already been outlined in Part 1, Section 1, and in particular in Table 5.

Environment, health & safety considerations

The protection of the environment is a cornerstone of EU policy, and provisions relating to health and safety – both to humans and ecosystems – are embedded across EU programmes, regulations and policies. For CCU technologies to gain public acceptance they will need to demonstrate that they are not harmful to the environment and do not pose significant health or safety risks. The analysis

---

18 Note that indirect effects may be extremely difficult to determine, or in potential conflict with other policy aims such as enhancing energy security (e.g. the potential for continuing dependence on fossil fuels through the use of CO₂-EHR)
outlined in Part 1, Section 4.4, suggests that the current evidence base indicates such potential impacts to be limited.

Alignment with EU energy policy

As described in Part 1, Section Error! Reference source not found., the EU’s long-term energy strategy is set out in the Energy Roadmap to 2050 (European Commission, 2011c). This section also highlighted that several CCU technologies have the potential to support long-term EU energy policy objectives, including enhancing security of energy supply. A strategy of improving energy security – through reducing fossil fuel import dependence – is closely aligned with policies aimed at promoting renewable energy and energy efficiency. Key considerations therefore include whether the technology:

- Has the ability to increase European energy security e.g. through substitution of fossil fuel-based products, and/or the promotion of indigenous energy resources;
- Has the ability to increase or stimulate more efficient use of energy;
- Support or stimulate the transition towards renewable energy (e.g. through the ability to provide a means of energy storage);
- Has the ability to store energy.

An associated and important consideration relates to the potential use of CO₂ as a raw material. Where CCU uses CO₂ as a direct feedstock, it has the ability to directly substitute the use of e.g. crude oil and other fossil fuel-based materials in the production process. This has important benefits in terms of energy security and resource use.
Annex C – Technology overviews

In this Annex the technology description and overview of the six (categories of) CCU technology overviews are presented, namely:

- Renewable methanol production;
- Formic acid production;
- Algae cultivation;
- CO$_2$ concrete curing
- Carbonate mineralisation (both cement and other), and;
- Polymer processing.

Note:
The technological descriptions and overviews are based on information from interviews and various studies, papers and corporate websites. The purpose of this assessment is to create an overview of the available information on the different CCU technologies. The project team cannot accept responsibility for any omissions, misrepresentations or misinterpretations of the literature, and third parties cannot rely on the information provided.
Renewable methanol

The electrolysis of water produces hydrogen ($H_2$), which is combined with $CO_2$, compressed and reacted over a metal/metal oxide catalyst to produce methanol and water. The separated methanol can e.g. be blended with different grades of gasoline for use as a transport fuel. Other energy applications include dimethyl ether (DME), biodiesel and methanol-to-power. The energy required by the process can be provided from a renewable energy source (GCSSI, 2011; Methanol Institute, 2012). Renewable methanol produced in such way could serve as storage medium for renewable energy.

Technological development

Over the last years, the technology development in renewable methanol has been developed from research towards the construction of a demonstration plant (full-scale). One of the most important developers of renewable methanol is Carbon Recycling International (CRI), an Icelandic company that has commissioned this plant beginning this year (2012).

For the production of methanol from $CO_2$ and hydrogen is needed. CRI has the largest electrolyser unit of Europe at their facilities. Their current production is 1.7 million litres of renewable methanol per year, which can be scaled-up to 5 million litres per year. This is considered industrial-scale. The methanol is blended with unleaded gasoline and sold at fuel stations throughout Reykjavik (CRI, 2012). See also Box 3 for more information about CRI.

Research activities are focusing on the integration of intermittent renewable sources, such as wind and solar and the development of Emissions-to-Liquids second generation (ETL2). ETL2 is focused on producing liquid alternative fuels out of waste streams. In this research, gasification of waste is combined with reusing $CO_2$. The project is currently at the pilot stage.

In the development of renewable methanol CRI is collaborating mostly with organisations that are not fully dedicated to the development of renewable methanol. Their partners include Iceland Oils (Olis) as the methanol customer; HS Orka as the geothermal energy and $CO_2$ feedstock provider and Century Aluminium as an industrial research partner (CRI, 2012). At the moment, limited companies are developing renewable methanol technology. This hampers the fast technology progress required to bring it to a competitive level.

There is increasing interest in renewable methanol from countries outside Iceland. The Danish government has performed a study to the best approach to replace fossil fuels. Methanol was ranked high, as one of the most cost-effective and sustainable solutions (Lund et al., 2011), amongst other as it could act as an effective medium for energy storage of intermittent renewable energy sources.

Despite the interest the use of renewable methanol in Europe is small, despite its significant potential. In the EU, blending of (renewable) methanol in conventional fuels is authorised up to 3%, which forms a substantial market. Moreover, it is technically possible to increase this blending rate, which would increase the market for renewable methanol significantly.
Renewable methanol is in principle eligible under the Renewable Energy Directive (RED), but its role is in practice limited. Interpretation of RED requires 100% renewable energy input in the production process, which may hinder application. In addition, Member States already have implemented biofuel mandates to achieve renewable energy targets for transportation fuels. This biofuel mandate seems sufficient to meet the targets and therefore there is no real incentive to use renewable methanol.

For the development of renewable methanol, limited funding for research is made available by the EU and in Nordic countries. CRI built their business without public funding, due to the specific circumstance in Iceland. So far, there are no experiences with public opposition against renewable methanol.

### Technology summary renewable methanol production

<table>
<thead>
<tr>
<th>Category</th>
<th>Description</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Technology/application</strong></td>
<td>Renewable methanol production (via water electrolysis)</td>
<td>1. Methanol Institute (2012); see <a href="http://www.methanol.org">www.methanol.org</a>; 2. GCCSI (2011)</td>
</tr>
<tr>
<td><strong>Brief description</strong></td>
<td>The electrolysis of water produces hydrogen, H2, which is combined with CO2, compressed and reacted over a metal/metal oxide catalyst to produce methanol and water. The separated methanol can be blended with different grades of gasoline for use as a transport fuel. The energy required by the process can be provided from a renewable energy source.</td>
<td>1. GCCSI (2011)</td>
</tr>
<tr>
<td><strong>Technology providers</strong></td>
<td>Carbon Recycling International; CRI (Iceland)</td>
<td></td>
</tr>
<tr>
<td><strong>CO2 sources and requirements</strong></td>
<td>Requires concentrated CO2 source e.g. flue gas from power plants and other industrial sources</td>
<td>1. GCCSI (2011)</td>
</tr>
<tr>
<td><strong>CO2 utilisation rate</strong></td>
<td>Estimated at approx. 3.5 tonnes per tonne of H2 (liquid) fuel produced</td>
<td></td>
</tr>
<tr>
<td><strong>Destination of CO2</strong></td>
<td>Not permanent; CO2 released upon end use fuel combustion</td>
<td></td>
</tr>
<tr>
<td><strong>Technology and project status</strong></td>
<td>Carbon Recycling International (CRI) has recently constructed a 2 million litres per annum plant in Iceland that will produce renewable methanol from CO2 captured from a local geothermal power station. The methanol is blended with unleaded gasoline and sold at Oli fuel stations throughout Reykjavik. The project involves several partners including Iceland Oils (Oli) as the methanol customer; HS Orka as the geothermal energy and CO2 feedstock provider and Century Aluminium as an industrial research partner. CRI plans to expand the facility to 5 million litres pa and also has plans to build commercial plants for export to other European countries; the company is currently planning a 50 million litres pa export plant.</td>
<td>1. CRI (2012); see <a href="http://www.carbonrecycling.is">www.carbonrecycling.is</a>; 2. GCCSI (2011)</td>
</tr>
<tr>
<td><strong>Estimated time to commercial deployment</strong></td>
<td>Renewable methanol production is ready for commercialisation, with the first commercial scale plant having recently been constructed in Iceland (November 2011). The objective of the first commercial CRI plant (5 million litres pa) is to gain operating experience and to improve plant economics for building larger plants (foreseen as 50 million litres pa as standard). It includes validation of distribution channels and logistics of Renewable Methanol for Iceland and the EU. In addition to the Icelandic programme, China has developed significant R&amp;D programmes for methanol and its derivative dimethyl ether as transport fuels (although not based upon renewable energy supply).</td>
<td>1. CRI (2012); see <a href="http://www.carbonrecycling.is">www.carbonrecycling.is</a>; 2. GCCSI (2011)</td>
</tr>
<tr>
<td><strong>R&amp;D programmes and objectives</strong></td>
<td>The objective of the first commercial CRI plant (5 million litres pa) is to gain operating experience and to improve plant economics for building larger plants (foreseen as 50 million litres pa as standard). It includes validation of distribution channels and logistics of Renewable Methanol for Iceland and the EU. In addition to the Icelandic programme, China has developed significant R&amp;D programmes for methanol and its derivative dimethyl ether as transport fuels (although not based upon renewable energy supply).</td>
<td>1. CRI (2012); see <a href="http://www.carbonrecycling.is">www.carbonrecycling.is</a>; 2. GCCSI (2011)</td>
</tr>
<tr>
<td><strong>Funding and support programmes</strong></td>
<td>The Innovation Center Iceland, the national laboratory under the Ministry of Industry potentially, is providing a 1 year grant and technology assistance to the CRI project.</td>
<td>1. The Reykjavik Grapevine (28 February, 2012); see <a href="http://grapevine.is/News/ReadArticle/Carbon-Recycling-In-Effect-Near-Blue-Lagoon">http://grapevine.is/News/ReadArticle/Carbon-Recycling-In-Effect-Near-Blue-Lagoon</a></td>
</tr>
</tbody>
</table>
Formic acid production

Electrochemical reduction of CO$_2$ combines captured CO$_2$ and water to produce formic acid (HCOOH) and O$_2$. The formic acid is used as a hydrogen carrier in fuel cells (for use in transportation; CHP units etc); hydrogen is released from the liquid formic acid as required when an aqueous solution of formic acid is exposed to an appropriate catalyst. The process requires electrical energy of around 8 MWh per tonne CO$_2$ used (Parsons Brinckerhoff/GCCSI, 2011; Science Daily, 2008).

**Current technological development**

Technological development of formic acid production reusing CO$_2$ is in an early stage. Currently, research is taking place at a lab-scale and is focused on fundamental chemistry. According to stakeholders, more research is needed to increase catalyst life, reducing energy consumption and increase production rates. These issues are currently being addressed by several stakeholders among which DNV. Significant technological advantages are needed to enhance large-scale use (DNV, 2011).

Demonstration of formic acid production is at pilot-scale at most. DNV is working on their ECFORM reactor (Electrochemical Reduction of CO$_2$ to Formate Formic Acid) to utilise renewable energy by reforming CO$_2$ to a commercially useful product (DNV, 2011). Another project, the CO$_2$rect project (CO$_2$ Reaction using Regenerative Energies and Catalytic Technologies), is a project in which basic

<table>
<thead>
<tr>
<th>Environment and economics</th>
<th>Market and economics</th>
<th>Cost factors</th>
<th>Sources of revenue generation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Life-cycle GHG emissions</td>
<td>Regional considerations</td>
<td>Cost factors</td>
<td>Sales of methanol to fuel suppliers.</td>
</tr>
<tr>
<td>Other environmental considerations</td>
<td>Current and future potential demand</td>
<td>Current and future potential demand</td>
<td>The plant investment cost is approx. USD 15 million. Production cost information is not available; however, the CRI programme is progressing on a commercial basis. The production economics strongly determined by the relative costs of (renewable) electricity and conventional fuels being displaced by the produced methanol (which are very low and very high, respectively, in Iceland).</td>
</tr>
</tbody>
</table>
| | | | 1. CRI (2012); see www.carbonrecycling.is;  
2. DG Environment; see http://ec.europa.eu/environment/energy/energy/energy.htm  
3. International Methanol Producers and Consumers Association; see http://www.impa.be/en/about_methanol  
4. GCCSI (2011)  
5. CRI (2012); see www.carbonrecycling.is;  
6. The Reykjavik Grapevine (28 February, 2012); see http://grapevine.is/News/ReadArticle/Carbon-Recycling-In-Effect-Near-Blue-Lagoon  
| | | | 1. CRI (2012); see www.carbonrecycling.is;  
| | | | 1. DG Environment; see http://ec.europa.eu/environment/energy/energy/energy.htm  
2. The Reykjavik Grapevine (28 February, 2012); see http://grapevine.is/News/ReadArticle/Carbon-Recycling-In-Effect-Near-Blue-Lagoon  
| Barriers to widespread deployment | | | 1. CRI (2012); see www.carbonrecycling.is;  

Electric vehicles: Regulations limiting renewable content in gasoline blends aim also to limit market development (e.g. the EU Fuel Quality Directive currently limits methanol content in transport fuels to 1%).
chemicals are produced from CO$_2$. The concept is to use a surplus electricity from regenerative renewable sources to produce hydrogen from water. This reacts with CO$_2$ captured from waste gases to from chemicals that can be used for chemicals storage (as in formic acid) or to produce high-performance chemicals (Bayer, 2010). This project is also entering the pilot-scale stage. Mantra Energy Venture (Canada) claims to be close to operating a demonstration project in South Korea (Parsons Brinckerhoff/GCCSI, 2011).

According to stakeholders, collaboration is not yet a very common practice in the development of formic acid production, but it is evolving.

Reusing CO$_2$ in the production process of formic acid has some advantages over the current production method. The most important is that formic acid production could be used as medium for energy storage (i.e. hydrogen). This would open up possibilities for use in fuel cells and could stimulate the renewable energy transition. Currently, CO$_2$ utilisation makes the production of formic acid more expensive, but it is expected that the combination of the electrochemical process with grid-base ancillary services can make these processes economically viable, even without a carbon price mechanism (DNV, 2011).

The current technological developments of formic acid are financially supported by both industrial companies (such as DNV and the CO$_2$rect consortium partners) and government grants (e.g. German Federal government).

Activities on the development of formic acid production are mainly focused on R&D. Creation of legitimacy for the technology is therefore not a major point of attention right now.

**Technology summary renewable formic acid production**
Mantra Energy Venture claims to be close to operating an ERC demonstration project in South Korea. Mantra is currently in agreement with École Polytechnique Fédérale de Lausanne’s (EPFL) Laboratory of Organometallic and Medicinal Chemistry (LCOM) and Granit Green Networks Ltd. (GGN) of Switzerland to engage in a collaborative project to demonstrate the full formic acid-to-hydrogen chain. Fuel cells powered directly by formic acid have also been developed - by Tekion for use in personal communication devices and lap top computers - and are being investigated at larger scale by Mantra.

<table>
<thead>
<tr>
<th>Technology/application</th>
<th>Description</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Formic acid production</td>
<td>Electrochemical reduction of CO₂ (ERC) combines captured CO₂ and water to produce formic acid (HCOOH) and O₂. The formic acid is used as a hydrogen carrier in fuel cells (for use in transportation; CHP units etc); hydrogen is released from the liquid formic acid as required when an aqueous solution of formic acid is exposed to an appropriate catalyst. The process requires electrical energy of around 8MWh per tCO₂ used.</td>
<td>1. GCCSI (2011); 2. Science Daily (2008); see <a href="http://www.sciencedaily.com/releases/2008/05/080507105630.htm">http://www.sciencedaily.com/releases/2008/05/080507105630.htm</a></td>
</tr>
<tr>
<td>Technology providers</td>
<td>Companies researching electrochemical reduction of CO₂ include Liquid Light Inc (US), DNV (Norway), and Mantra Venture Group (Canada). Liquid Light’s work is based on research at Princeton University, where the research group have developed homogeneous catalysts that allow for conversion of CO₂ to formic acid, methanol, propargyl, and butane, and other chemicals. DNV, in partnership with Ohio State University and the Mantra Venture Group are both developing CO₂ to formic acid systems based on tin or tin-based alloy cathodes. Mantra Venture Group (Mantra) claims to be close to operating an ERC demonstration project in South Korea. Mantra is currently in agreement with École Polytechnique Fédérale de Lausanne’s (EPFL) Laboratory of Organometallic and Medicinal Chemistry (LCOM) and Granit Green Networks Ltd. (GGN) of Switzerland to engage in a collaborative project to demonstrate the full formic acid-to-hydrogen chain. Fuel cells powered directly by formic acid have also been developed - by Tekion for use in personal communication devices and lap top computers - and are being investigated at larger scale by Mantra.</td>
<td>1. Wikipedia (01/05/12); see <a href="http://en.wikipedia.org/wiki/Electrochemical_reduction_of_carbon_dioxide">http://en.wikipedia.org/wiki/Electrochemical_reduction_of_carbon_dioxide</a> 2. Mantra Energy (01/05/2012); see <a href="http://www.mantranergy.com/Portal/View/MantraEnergy/pdf/articles/formic%20acid%20opportunities.pdf">http://www.mantranergy.com/Portal/View/MantraEnergy/pdf/articles/formic%20acid%20opportunities.pdf</a> 3. Mantra Energy (01/05/2012); see <a href="http://www.mantranergy.com/Press/PressReleases/tabid/3550/articleType/Article">http://www.mantranergy.com/Press/PressReleases/tabid/3550/articleType/Article</a> View/articleId/29/Mantra-Venture-Group-Ltd-To-Collaborate-With-Ecole-Polytechnique-Federale-de-Lausanne’s-Laboratory-of-Organometallic-And-Medicinal-Chemistry-and-Grant-Green-Networks-Ltd.aspx 4. DNV (2011); see <a href="http://www.dnv.com/binaries/dnv-position_paper_co2_utilisation_tcm4-445820.pdf">http://www.dnv.com/binaries/dnv-position_paper_co2_utilisation_tcm4-445820.pdf</a> 5. Liquid Light Inc (2012); see <a href="http://liquidlightinc.com/about.html">http://liquidlightinc.com/about.html</a></td>
</tr>
<tr>
<td>CO₂ sources and requirements</td>
<td>Requires concentrated CO₂ source e.g. flue gas from power plants and other industrial sources</td>
<td>1. GCCSI (2011)</td>
</tr>
<tr>
<td>CO₂ utilisation rate</td>
<td>Estimated at approx. 3.1 tonnes per tonne of H₂ (liquid) fuel produced</td>
<td>1. GCCSI (2011)</td>
</tr>
<tr>
<td>Destination of CO₂</td>
<td>Not permanent; CO₂ released upon end use fuel combustion. However, capture could be theoretically possible for application in stationary fuel cells e.g. CHP.</td>
<td>1. GCCSI (2011)</td>
</tr>
<tr>
<td>Technology and project status</td>
<td>Mantra Energy Venture claims to be close to operating an ERC demonstration project in South Korea. However, as yet there are no known plans for developing the formic acid to H₂ part of the chain, other than at R&amp;D stage. It has been demonstrated (using for example a ruthenium catalyst and an aqueous solution of formic acid) by several research teams and could be pursued commercially in the future should the CO₂ to formic acid part of the chain prove successful.</td>
<td>1. GCCSI (2011)</td>
</tr>
<tr>
<td>Estimated time to commercial deployment</td>
<td>Mantra are currently pursuing patents for their ERC technology in Canada, Australia, China, Japan, Europe and the United States and in May 2012 were granted a patent in India. The commercial deployment of formic acid as a hydrogen fuel carrier likely to be at least 10 years away, since the formic acid to hydrogen component of the chain remains at R&amp;D stage only. Mantra claim that commercial scale plants will be operational within 4 to 5 years (producing the formic acid as a hydrogen energy carrier, but not extracting the hydrogen).</td>
<td>1. Mantra Energy (2012); see <a href="http://www.mantranergy.com/Portal/View/MantraEnergy/pdf/articles/formic%20acid%20opportunities.pdf">http://www.mantranergy.com/Portal/View/MantraEnergy/pdf/articles/formic%20acid%20opportunities.pdf</a> 2. Mantra Energy (2012); see <a href="http://www.mantranergy.com/Economics/ComparisonsWithCCS.aspx">http://www.mantranergy.com/Economics/ComparisonsWithCCS.aspx</a></td>
</tr>
<tr>
<td>R&amp;D programmes and objectives</td>
<td>The Mantra ERC team has been focused since 2009 on increasing the cathode utilisation rate e.g. reducing formate cross-over to retrieve formate from the catholyte solution, and optimizing the formic acid synthesis.</td>
<td>1. Wikipedia (01/05/12); see <a href="http://en.wikipedia.org/wiki/Electrochemical_reduction_of_carbon_dioxide">http://en.wikipedia.org/wiki/Electrochemical_reduction_of_carbon_dioxide</a> 2. Mantra Energy (2012); see <a href="http://www.mantranergy.com/Economics/ComparisonsWithCCS.aspx">http://www.mantranergy.com/Economics/ComparisonsWithCCS.aspx</a></td>
</tr>
<tr>
<td>Funding and support programmes</td>
<td>The National Research Council of Canada Industrial Research Assistance Program (NRC-IRAP) agreed to fund 50 per cent of the costs associated with the development of Mantra’s ERC technology in May 2009.</td>
<td>1. Wikipedia (01/05/12); see <a href="http://en.wikipedia.org/wiki/Electrochemical_reduction_of_carbon_dioxide">http://en.wikipedia.org/wiki/Electrochemical_reduction_of_carbon_dioxide</a></td>
</tr>
</tbody>
</table>
Currently, sales of formic acid and ultimately sales of hydrogen fuel. Current prices for formic acid are around US$1,440 per tonne. 

Cost factors

Mantra claims that the ERC system (excluding the formic acid to hydrogen stage) is currently profitable according to ROI estimates. They also claim that the ERC technology could provide a net revenue of up to US$700 per tonne of CO₂ used. However, for the full chain, there is a lack of information about the technology’s potential economic feasibility. It has been estimated (GCCSI, 2011) that on an energy equivalent basis, the formic acid produced for use as a liquid fuel would be priced at US$210/t formic acid, or US$338/t CO₂ input which would require an electricity price of US$42/kWh or less to break even on the production price alone. Commercial viability will also depend on the additional costs of CO₂ handling (e.g. capture and transport). DNV indicates that the energy costs for their ECOFORM process are in the range of US$270-578 per ton of formic acid against an assumed market price for formic acid of US$1,220 per ton.

Current and future potential demand

The current formic acid market is 650,000tpa according to Mantra. The CO₂ content of formic acid (equivalent) is 96 per cent by mass, e.g. 622,000tpa. The current market for formic acid, although growing, would constitute a relatively small consumption of CO₂, even if the entire current production system were to be replaced with ERC. Potential use as a fuel carrier is therefore of greater interest. The scale-up potential is significant; displacement of 1 per cent of the world’s fossil petroleum consumption with hydrogen carried by formic acid would represent in excess of 10tpa CO₂ recycling. GCCSI (2011) estimates cumulative global demand for CO₂ use in formic acid production to 2020 to be less than 5 Mt; further future potential is estimated to be greater than 300 Mt per year.

Market development factors

The global market for formic acid is relatively small, with an immediate market size of approximately $1 billion (Mantra Energy, 2012). If the use of formic acid as a liquid fuel for transportation can be proved successful there is a large potential for entry into the market. However, given that current alternatives, such as petroleum, are currently trading at relatively low prices of $2/litre displacing these alternatives given the current estimates appears to be unlikely at present.

Regional considerations

Since the energy input to the ERC system is electrical energy, production is possible anywhere in proximity to a high concentration CO₂ source and an electricity network (although renewable energy supply is key from a carbon balance perspective). Production of formic acid is largely dominated by Western Europe; BASF (Germany) is the world’s largest producer of formic acid, producing approximately 182,000 tpa. Kemira Oyj (Finland) produces in excess of 100,000 tpa in Finland and is the world’s second largest producer. Neither company is currently profitable according to ROI estimates. They also claim that the ERC technology could provide a net revenue of up to US$700 per tonne of CO₂ used.

Barriers to widespread deployment

Key barriers are those relating more broadly to the use of hydrogen fuel; high production costs, challenges to developing fuel distribution infrastructure, and public acceptability. ERC fuel cells would also need to compete economically with existing lower cost fuel alternatives such as petroleum and alternative low carbon transport technologies such as electric vehicles and biofuels already in commercial development.

Life-cycle GHG emissions

The life-cycle GHG emissions depend upon the electricity source used in the ERC process. GCCSI (2011) estimates that for a dedicated renewable electricity source, additional CO₂ emissions would be less than 0.5 tCO₂e per tCO₂ used. Case study results based on the Mantra Energy project (capture from a coal-fired power station in South Korea, supplying CO₂ to the electrolysis plant via a 9km pipeline) indicate additional emissions of 3.36 tCO₂e per tCO₂ used (Edge Environment Case Study, 2011). In August 2009, Mantra Energy completed a preliminary carbon balance report on its ERC technology, entitled “Possible Reactions Related to Carbon Credits – ERC Process of Mantra Energy.” The analysis determined that one tonne of formic acid formed through ERC effectively “sequesters” approximately 0.95 tonnes of CO₂, assuming that the formic acid is then incorporated into compounds with a long lifetime.

Other environmental considerations

Unknown.

ENVIRONMENT MARKET AND ECONOMICS

Sources of revenue generation

Currently, sales of formic acid and ultimately sales of hydrogen fuel. Current prices for formic acid are around US$1,440 per tonne. 

Cost factors

Mantra claims that the ERC system (excluding the formic acid to hydrogen stage) is currently profitable according to ROI estimates. They also claim that the ERC technology could provide a net revenue of up to US$700 per tonne of CO₂ used. However, for the full chain, there is a lack of information about the technology’s potential economic feasibility. It has been estimated (GCCSI, 2011) that on an energy equivalent basis, the formic acid produced for use as a liquid fuel would be priced at US$210/t formic acid, or US$338/t CO₂ input which would require an electricity price of US$42/kWh or less to break even on the production price alone. Commercial viability will also depend on the additional costs of CO₂ handling (e.g. capture and transport). DNV indicates that the energy costs for their ECOFORM process are in the range of US$270-578 per ton of formic acid against an assumed market price for formic acid of US$1,220 per ton.

Current and future potential demand

The current formic acid market is 650,000tpa according to Mantra. The CO₂ content of formic acid (equivalent) is 96 per cent by mass, e.g. 622,000tpa. The current market for formic acid, although growing, would constitute a relatively small consumption of CO₂, even if the entire current production system were to be replaced with ERC. Potential use as a fuel carrier is therefore of greater interest. The scale-up potential is significant; displacement of 1 per cent of the world’s fossil petroleum consumption with hydrogen carried by formic acid would represent in excess of 10tpa CO₂ recycling. GCCSI (2011) estimates cumulative global demand for CO₂ use in formic acid production to 2020 to be less than 5 Mt; further future potential is estimated to be greater than 300 Mt per year.

Market development factors

The global market for formic acid is relatively small, with an immediate market size of approximately $1 billion (Mantra Energy, 2012). If the use of formic acid as a liquid fuel for transportation can be proved successful there is a large potential for entry into the market. However, given that current alternatives, such as petroleum, are currently trading at relatively low prices of $2/litre displacing these alternatives given the current estimates appears to be unlikely at present.

Regional considerations

Since the energy input to the ERC system is electrical energy, production is possible anywhere in proximity to a high concentration CO₂ source and an electricity network (although renewable energy supply is key from a carbon balance perspective). Production of formic acid is largely dominated by Western Europe; BASF (Germany) is the world’s largest producer of formic acid, producing approximately 182,000 tpa. Kemira Oyj (Finland) produces in excess of 100,000 tpa in Finland and is the world’s second largest producer. Neither company is currently profitable according to ROI estimates. They also claim that the ERC technology could provide a net revenue of up to US$700 per tonne of CO₂ used.

Barriers to widespread deployment

Key barriers are those relating more broadly to the use of hydrogen fuel; high production costs, challenges to developing fuel distribution infrastructure, and public acceptability. ERC fuel cells would also need to compete economically with existing lower cost fuel alternatives such as petroleum and alternative low carbon transport technologies such as electric vehicles and biofuels already in commercial development.

Life-cycle GHG emissions

The life-cycle GHG emissions depend upon the electricity source used in the ERC process. GCCSI (2011) estimates that for a dedicated renewable electricity source, additional CO₂ emissions would be less than 0.5 tCO₂e per tCO₂ used. Case study results based on the Mantra Energy project (capture from a coal-fired power station in South Korea, supplying CO₂ to the electrolysis plant via a 9km pipeline) indicate additional emissions of 3.36 tCO₂e per tCO₂ used (Edge Environment Case Study, 2011). In August 2009, Mantra Energy completed a preliminary carbon balance report on its ERC technology, entitled “Possible Reactions Related to Carbon Credits – ERC Process of Mantra Energy.” The analysis determined that one tonne of formic acid formed through ERC effectively “sequesters” approximately 0.95 tonnes of CO₂, assuming that the formic acid is then incorporated into compounds with a long lifetime.

Other environmental considerations

Unknown.
Algae cultivation

Algae cultivation is being developed in Europe for several years. The essence of algae cultivation is to develop systems that facilitate the growth of algae. There are basically two types of systems: open systems (in raceway ponds, shallow lagoons or open water) making use of the natural CO₂ uptake of algae and closed systems in which CO₂ concentrations are increased to accelerate the growth process.

Both technologies can be regarded as CO₂ reuse, although there are major differences. Natural systems absorb CO₂ from the atmosphere, using the natural process of reusing CO₂. These systems have a great potential to be used in open water, once the systems can be made floatable. Closed systems can be used to utilise CO₂ captured from flue gas of point sources.

Current status technological development

In Europe several R&D projects to develop algae cultivation systems have been deployed over the past years including a variety of stakeholders. Typical stakeholders in the stage of R&D are universities (e.g. Wageningen University, Ben Gurion University, Bielefeld University) and research institutes (e.g. VITO, Fraunhofer Umsicht Institute, Max Planck Institute). In 2010 a call to develop algae cultivation was opened under FP7, resulting in three industry-led consortia awarded with funds with a total value of €31 million¹⁹: BIOFAT, All Gas and InteSusAl. These projects have the objective to demonstrate the production of algal biofuels along the whole value chain. Other European algae projects are listed in Box 2.

As mentioned above, fundamental research is performed to improve scalability, improving bioconversion rates and making the technology floatable. In most of the algae cultivation projects atmospheric CO₂ is used to grow algae, such as projects from Subitec (developing the technology to increase algae production) and Abengoa (started in 2011 with the construction of their ECOALGA project) (European Biofuels, 2012). Integration of CO₂ captured from point sources in the algae cultivation systems is not very common. An Austrian company called SAT (See Algae Technology) is currently developing a biofuel plant producing seaweed (macro algae) using the CO₂ captured from an adjacent sugar cane to ethanol plant in Brazil (European Biofuels, 2012).

The most important goal of current projects is to lower both CAPEX and OPEX of algae cultivation, which is a pre-requisite to compete on mass markets such as food and energy. Cultivation and harvesting costs are currently very high for most technology routes.

Collaboration between the different stakeholders on the development of algae cultivation technologies is currently quite high. Academic institutions, research institutes, start-ups and SMEs are involved in the development of the technology. One of the drivers for collaboration is for instance the FP7 projects, where collaboration is a funding requirement.

¹⁹ The total costs of the three projects are €31 million, of which €20.5 million from the European Commission (AlgaeCluster, 2012).
Besides collaborations, knowledge is exchanged during stakeholder meetings, conferences and workshops. Numerous events have been organised by the algae community during the past years and different network organisations and associations have been established to stimulate the development of algae cultivation. A few examples are:

- European Biofuels technology platform;
- NETALGAE network (http://www.netalgae.eu/netalgae-project.php);
- European Algae Biomass Association – EABA (http://www.eaba-association.eu/);
- European Biomass Industry Association – EnAlgae (http://www.enalgae.eu/european-biomass-industry-association.htm);

One of the important drivers for the development of algae cultivation systems are expectations on the importance of algae. These expectations vary between stakeholders and algae products. Some think that algae will play a marginal role at best, others have high expectation on the role of algae in biofuels (Parsons Brinckerhoff/GCCSI, 2011). The role for algae will become increasingly important for two main reasons:

- Algae can be used for a wide variety of products including biofuels, chemistry and food;
- Algae cultivation has the potential to make use of water bodies as farming grounds, expanding the possibilities for biomass cultivation.

Besides the technological developments, less attention is paid to activities concerning market creation and creation of legitimacy. The European market for algae products is developing slowly, especially when compared to North America and Asia. In these regions, algae have a positive and healthy image and are already commonly used in food, supplements and dermo-beauty products. Compared to other markets the growth potential for algae in Europe is large, but growing slowly. One of the barriers that is noticed by stakeholders that is hampering the use of algae in food is that authorisation processes for algae species to be used in food is complex. The wide variety of algae species is making this process even more complex.
## Technology summary renewable formic acid production

<table>
<thead>
<tr>
<th>Technology/application</th>
<th>Description</th>
<th>References</th>
</tr>
</thead>
</table>

### Brief description
Algae can potentially be used to produce oil for use in alternative transport fuels, as well as for use as solid fuel biomass. Bubbling of CO₂ through algae cultivation systems can significantly increase algal yields, resulting in the production of biomass. Algae can be grown in shallow lagoons or raceway ponds on marginal land (e.g. Sapphire Energy, Aurora BioFuels, Live fuels) or closed ponds (e.g. Petrosun, Green Star). Green Star also produces a micronutrient formula to greatly increase the rate of algal growth. Plastic tubes in ponds developed by Solix BioFuels (with BASF) offer “up to 7 times the productivity” of open ponds. A number of closed photobioreactors are being investigated, including: Horizontal tubes (e.g. AlgaeLink NV), Vertical (e.g. NOVAgreen Projektmanagement GmbH, Biofuel Systems SL), Thin film (e.g. GreenFuel Technologies), Open/Closed systems (e.g. Petro Algae, HR Biopetroleum). Algae may also be grown heterotrophically (in the absence of light) using sugar or cellulosic biomass for energy and carbon (e.g. Solazyme closed bioreactor).

### Technology providers
There are a large number of companies currently working on algae-derived biofuels (see above), across a range of technologies e.g. open ponds, closed ponds, photobioreactors.


### CO₂ sources and requirements
The process can operate on both dilute and concentrated CO₂ sources. However, algae cultivation systems are sensitive to certain components and impurities; captured CO₂ would likely need to be of high purity e.g. food-grade CO₂. According to GCCSI (2011), commercial scale systems in the region of 30-100Ha may absorb anything between 500 and 55,000 tCO₂ per year per system.

1. GCCSI (2011)

### CO₂ utilisation rate
According to GCCSI (2011), typically around 1.8–2.0 tonnes of CO₂ will be used per tonne of algal biomass produced (dry), although this rate varies with algal species and process.

1. GCCSI (2011)

### Destination of CO₂
Not permanent; the carbon is released upon end-use fuel combustion. May be semi-permanent for the production of other end products.
## Technology and project status

The use of recycled CO₂ for algae cultivation is still in the early research and development stages. At present, there are no closed algal cultivation systems for biomass/biofuel production operating at a commercial scale. However, there are many emerging at pilot or demonstration scale. Several major energy companies including BP, Chevron, and Shell have invested research funding into various systems and are carrying out feasibility studies. Most existing algal systems typically produce high-value nutraceuticals. At present there are no systems that can reliably produce algal biomass year round on a large industrial scale with the necessary yields for meaningful energy production, however recent activity and investment in the sector is high developing rapidly. RWE’s pilot project using CO₂ captured from its lignite-powered plant in Niederaussem, Germany was completed at the end of 2011 (run from 2008–2011); expansion of the project is now envisaged and there are several EC-funded demo projects including the BROAT demonstration project, The ALG-11 project and the InstiLux project. In 2011, Algenol started construction work at the ECOSLGA project plant in Cartagena. The 5000m² experimental plant will be supplied with CO₂ generated by the neighboring bioethanol facility. The project will evaluate strains of microalgae and cyanobacteria, harvesting technique, optimum CO₂ concentrations etc, for the production of biofuels and animal feed. The ECOSLGA Project has received funding from the Ministry of Science and Innovation, under the National Plan for Scientific Research, Development and Technological Innovation (PIER).

### Estimated time to commercial deployment

There are many operational and technical issues to resolve before a large-scale system competitive with crude oil can be operated. The industry consensus is that commercialisation is at least 5–10 years away. However, Solazyme claim to be already producing large volumes of oil already and have signed high profile deals with large corporations including Unilever, Chevron and the US Navy. In 2010, they delivered over 80,000 liters of algal-derived marine diesel and jet fuel to the U.S. Navy and were awarded another contract with the U.S. Department of Defense for production of up to 150,000 additional liters of algal-derived naval distillate. MBD claim to have reached agreements for pilot plants to be established at three coal-fired power stations in Australia; commercial scale operation is targeted for 2013 at an 80Ha scale, with a plan to introduce a demonstration plant by 2015.

### R&D programmes and objectives

Research is broad and spans several decades of investigation. Research studies over the years have investigated a variety of cultivation and processing options and have identified numerous potential output markets. A major area of research is to identify a ‘lipid trigger’ e.g. genetically modifying strains to produce more oil. A challenge is not only cultivating the algae itself but in extracting useful products through application of efficient harvesting and processing techniques. Since 2007, there has been an explosion of research institutes worldwide investigating algae, mostly driven by the commercial opportunity inherent in capturing even a fraction of the liquid transport fuel market. Israel, Japan, China and the US have a long track record in algae research, with Australia and NZ now also emerging with several large industry-based collaborations. Within Europe, algae-based biofuels form one of the value chains proposed in the European Bioenergy Industrial Initiative (EBII). Companies and universities involved in algal biofuels R&D&D are listed on the EIBI website.

### Funding and support programmes

Several multibillion dollar programs now exist driven by multinational energy companies, with large multi-disciplinary research collaborations now underway at a number of universities in the US, Australia, NZ, Japan, China, South Africa and Europe. The Mexican government has provided significant support to Algenol and Biofields for a project in the Sonora desert (an US$810 million algae plant). It is estimated that around 6 million tonnes of CO₂ per year will be reused which will in turn produce up to 1 billion gallons of ethanol (170,000 acres at 6,000 gallons per acre). The EC has announced results of the FP7 call on innovation in algae biofuels and has awarded €1.2 million to 5 teams. Companies and universities involved in algal biofuels R&D&D are listed on the EIBI website.

---

2. GCCSI (2011); 2. GCCSI (accessed 11 May 2012); see http://www.biofuelstp.eu/algae.html
4. GCCSI (2011); 2. GCCSI (accessed 11 May, 2012); see http://www.biofuelstp.eu/algae.html
5. GCCSI (2011); 1. GCCSI (2011); 2. GCCSI (accessed 11 May 2012); see http://www.biofuelstp.eu/algae.html
The produced biomass can be used to produce a wide range of products. Commonly, the natural oil fraction is sought as a feedstock for biodiesel production, food products, chemicals, nutraceuticals or for cracking into smaller base units before reforming to a wide range of other products. MDB Energy claim that every million tonnes of captured and recycled industry CO2 can generate about $150 million in earnings from the sales of transport oil and animal meal sales. Algae may be used to produce biofuels in several ways: Conversion to bioethanol (e.g. Algenol); extraction of oils (e.g. SGI, Sola Biofuels, Sapphire Energy, Algasol); production of oils from feedstock via dark fermentation (e.g. Solazyme); oil plus ethanol (e.g. PetroSun, Green Star); conversion of whole algae to biocrude via pyrolysis (e.g. BioFuel Systems SL); jet fuel (e.g. Sapphire Energy); algal biorefinery - biofuels and other products (Petroleum Algae, HI Biopetrosum).

Cost factors
Algae farms are large and expensive with some researchers estimating capital costs of US$16,000 per hectare and US$4,800 per hectare per annum of operating costs (Campbell et al 2009). The further CO2 capture and transport costs require additional capital and operating funding.

Current and future potential demand
Cultivation of algae for biofuel production has extremely high potential for very large scale reuse of CO2. GCCSI (2011) estimates that annual CO2 demand could be between 5 and 20Mt by 2030. It is forecast that by 2022, algae biofuels will be the largest biofuel category overall, accounting for 40 billion of the estimated 109 billion gallons of biofuels produced (Bradford, 2009). Europe is currently the world’s largest biodiesel market, and is expected to be worth US$7.0 billion by 2014. In 2008, The EU produced around 5m tonnes of biodiesel against a capacity of around 10 million tonnes. Emerging Markets Online (Biodiesel to 2020 - A Global Market Survey; Algae 2020) forecasts that while EU production of biodiesel will decline by around one half to 2 million barrels per day by 2030, demand will increase to over 15 million barrels per day. As well as the EU, China, India and the US have growing biofuels markets with policy targets for increased usage. Similarly, the IEA suggest that while the use of food crops is likely to decrease in the future, second and third generation biofuels based on algae and grasses will increase in supply; they project that by 2050, biomass-based sources could supply about 50% of the world’s energy requirements.

Market development factors
Algal oil has potential in many of the world’s largest markets including transportation fuel, livestock feed, agricultural fertiliser, oleo-chemicals, as well as pharmaceutical and nutraceuticals markets. The largest expected growth market for algae is biodiesel. MDB Energy estimates a total algal biofuels market worth of 1.6 billion (USD) in 2015. This indicates a 45% annual growth rate between 2010 and 2015. Because the entire algae biomass can be used for value capture, the production process can be quickly and efficiently tailored to adjust to changing market demands. Algal oil can also be injected into existing crude oil refineries. The ‘food versus biomass’ issues associated with many first generation biofuels are avoided with algal biofuels. A desire for energy security (specifically, transport fuel) and high volume CO2 abatement are key drivers in the push for algal oil.

Regional considerations
Solar irradiance and available land are the key factors determining algae growth potential, limiting its use in many world regions. Algal oil can be injected into existing crude oil refineries.

Barriers to widespread deployment
Competition from crude oil derived products (algae systems are highly exposed to fluctuations in the price of fossil crude); land availability. There are also various technical and reliability barriers to overcome through ongoing R&D efforts.

Life-cycle GHS emissions
One LCA case study analysis indicates around 0.02 kg CO2 e of additional emissions per tonne of CO2 reused, based on an algae farm integrated with a coal-fired power station in Eastern Australia (based on process requirements similar to those identified in public documents of MDB Energy).

Other environmental considerations
Algae cultivation systems can be used as a step in waste water treatment e.g. removing certain compounds from wastewater/sewage. Biochar, which can be a by-product can be used as a soil conditioner. Algal meal used as a livestock feed can also be used to reduce methane emissions.

1. IEA (2011) - An Assessment of the Current Status and Potential for Algal Biofuels Production; see http://www.task39.org/LinkClick.aspx?fileticket=esGoBD1Q9BY%3d&tabid=4348; GCCSI (2011)
1. GCCSI (2011); 2. MDB Energy (www.mdbenergy.com); 3. European Biofuels Technology Platform, Algae Task Force; see http://www.biofuelstp.eu/algae.html

MARKET AND ECONOMICS

ENVIRONMENT

Sources of revenue generation
The produced biomass can be used to produce a wide range of products. Commonly, the natural oil fraction is sought as a feedstock for biodiesel production, food products, chemicals, nutraceuticals or for cracking into smaller base units before reforming to a wide range of other products. MDB Energy claim that every million tonnes of captured and recycled industry CO2 can generate about $150 million in earnings from the sales of transport oil and animal meal sales. Algae may be used to produce biofuels in several ways: Conversion to bioethanol (e.g. Algenol); extraction of oils (e.g. SGI, Sola Biofuels, Sapphire Energy, Algasol); production of oils from feedstock via dark fermentation (e.g. Solazyme); oil plus ethanol (e.g. PetroSun, Green Star); conversion of whole algae to biocrude via pyrolysis (e.g. BioFuel Systems SL); jet fuel (e.g. Sapphire Energy); algal biorefinery - biofuels and other products (Petroleum Algae, HI Biopetrosum).

Cost factors
Algae farms are large and expensive with some researchers estimating capital costs of US$16,000 per hectare and US$4,800 per hectare per annum of operating costs (Campbell et al 2009). The further CO2 capture and transport costs require additional capital and operating funding.

Current and future potential demand
Cultivation of algae for biofuel production has extremely high potential for very large scale reuse of CO2. GCCSI (2011) estimates that annual CO2 demand could be between 5 and 20Mt by 2030. It is forecast that by 2022, algae biofuels will be the largest biofuel category overall, accounting for 40 billion of the estimated 109 billion gallons of biofuels produced (Bradford, 2009). Europe is currently the world’s largest biodiesel market, and is expected to be worth US$7.0 billion by 2014. In 2008, The EU produced around 5m tonnes of biodiesel against a capacity of around 10 million tonnes. Emerging Markets Online (Biodiesel to 2020 - A Global Market Survey; Algae 2020) forecasts that while EU production of biodiesel will decline by around one half to 2 million barrels per day by 2030, demand will increase to over 15 million barrels per day. As well as the EU, China, India and the US have growing biofuels markets with policy targets for increased usage. Similarly, the IEA suggest that while the use of food crops is likely to decrease in the future, second and third generation biofuels based on algae and grasses will increase in supply; they project that by 2050, biomass-based sources could supply about 50% of the world’s energy requirements.

Market development factors
Algal oil has potential in many of the world’s largest markets including transportation fuel, livestock feed, agricultural fertiliser, oleo-chemicals, as well as pharmaceutical and nutraceuticals markets. The largest expected growth market for algae is biodiesel. MDB Energy estimates a total algal biofuels market worth of 1.6 billion (USD) in 2015. This indicates a 45% annual growth rate between 2010 and 2015. Because the entire algae biomass can be used for value capture, the production process can be quickly and efficiently tailored to adjust to changing market demands. Algal oil can also be injected into existing crude oil refineries. The ‘food versus biomass’ issues associated with many first generation biofuels are avoided with algal biofuels. A desire for energy security (specifically, transport fuel) and high volume CO2 abatement are key drivers in the push for algal oil.

Regional considerations
Solar irradiance and available land are the key factors determining algae growth potential, limiting its use in many world regions. Algal oil can be injected into existing crude oil refineries.

Barriers to widespread deployment
Competition from crude oil derived products (algae systems are highly exposed to fluctuations in the price of fossil crude); land availability. There are also various technical and reliability barriers to overcome through ongoing R&D efforts.

Life-cycle GHS emissions
One LCA case study analysis indicates around 0.02 kg CO2 e of additional emissions per tonne of CO2 reused, based on an algae farm integrated with a coal-fired power station in Eastern Australia (based on process requirements similar to those identified in public documents of MDB Energy).

Other environmental considerations
Algae cultivation systems can be used as a step in waste water treatment e.g. removing certain compounds from wastewater/sewage. Biochar, which can be a by-product can be used as a soil conditioner. Algal meal used as a livestock feed can also be used to reduce methane emissions.

1. GCCSI (2011); 2. MDB Energy (www.mdbenergy.com); 3. European Biofuels Technology Platform, Algae Task Force; see http://www.biofuelstp.eu/algae.html
1. IEA (2011) - An Assessment of the Current Status and Potential for Algal Biofuels Production; see http://www.task39.org/LinkClick.aspx?fileticket=esGoBD1Q9BY%3d&tabid=4348; GCCSI (2011)
1. GCCSI (2011); 2. MDB Energy (www.mdbenergy.com); 3. European Biofuels Technology Platform, Algae Task Force; see http://www.biofuelstp.eu/algae.html

MARKET AND ECONOMICS

ENVIRONMENT

Sources of revenue generation
The produced biomass can be used to produce a wide range of products. Commonly, the natural oil fraction is sought as a feedstock for biodiesel production, food products, chemicals, nutraceuticals or for cracking into smaller base units before reforming to a wide range of other products. MDB Energy claim that every million tonnes of captured and recycled industry CO2 can generate about $150 million in earnings from the sales of transport oil and animal meal sales. Algae may be used to produce biofuels in several ways: Conversion to bioethanol (e.g. Algenol); extraction of oils (e.g. SGI, Sola Biofuels, Saphi...
Cement production
CCU opens up various possibilities for cement production. Captured CO₂ can react with alkaline water to form soluble carbonates. After removing the water, the remaining solids can be used in a number of construction applications. This specific process is called the Calera process, but other processes for cement production utilising CO₂ are possible too (Calera, 2012).

Several high tech firms are focusing on producing carbon negative cement by eliminating or reducing the carbon emissions that would otherwise be generated and emitted during manufacture of conventional (Portland) cement and by absorbing CO₂ with magnesium hydroxide (Mg(OH)_2) to create carbonates. CO₂ can also be absorbed from the atmosphere during the concrete curing process (Parsons Brinckerhoff/GCCSI, 2011; Shell, 2012). During the concrete curing phase in which the cement gains strength and hardens fully, CCU technology can be used to accelerate the process (Parsons Brinckerhoff/GCCSI, 2011; Shell, 2012).

Technological development phase
The development of CCU technologies in cement production is in a pre-commercial phase. Technology developers expect that the technology will become commercially available in about 5 years. Currently, the technology is being developed in small corporations that are focused on the development of this technology (Calera, Calix, Novacem, Carbon Sense Solutions, etc.).

Projects to develop CCU technologies for cement production are moving towards demonstrations. On concrete curing, Carbon Sense Solutions (Canada) is using CO₂ from onsite flue gases and local combustion sources are used to cure precast concrete products. By using high concentrations of CO₂, the process is accelerated, with claimed equal material performance to traditional the curing process (Parsons Brinckerhoff/GCCSI, 2011). In cement production, Calera has developed their products from pilot-scale demonstrations up to large-scale demonstrations and are currently preparing to demonstrate their products commercially (Calera, 2012). In Europe, UK company Novacem was active in the development cement production technologies. Novacem has received funding from different organisations or funds. In 2009 the company received £1.1 million seed money from a syndicate, it won a £1.5 million collaborative R&D grant from TSB and another £1.6 million in follow-up funding. With this money Novacem was able to finance its pilot-facility (IPPR, 2012). They built a pilot facility capable of a production of 4-5 tonnes of carbon-negative cement each year (IPPR, 2012).

Novacem experienced that it is hard to obtain venture capital and that there is a shortage of government support for mid-stage firms like Novacem. Potential investors are reluctant because of long payback period, which has an effect of the progress made in technological development (IPPR, 2012). In October 2012 Novacem closed their business and sold their intellectual property to Calix (Novacem, 2012).

---

20 In October 2012, Novacem announced that the company has been shut down and the Intellectual Property has been sold to Calix Limited (http://novacem.com/wp-content/uploads/2012/10/Novacem.16-October-2012.pdf). Novacem was approached for an interview, but it became clear that the company was going bankrupt in a matter of weeks. The interview got cancelled. No other companies were found in Europe, only outside.
The potential for CO$_2$ utilisation in the cement industry is huge. In the production process the net uptake of CO$_2$ is between 30-100 kg CO$_2$ per tonne of cement. Compared to Portland up to 850 kg of CO$_2$ emissions can be reduced per tonne cement (IPPR, 2012). The cement industry is responsible for 5% of the global CO$_2$ emissions and it is expected that the demand will double from now until 2050. Furthermore, the cement or concrete in which the CO$_2$ is sequestered is used for construction work and will therefore store the CO$_2$ for a significant amount of time. This means that if these cement production technologies will be rolled-out on a large scale, this can have a significant effect on the CO$_2$ emissions.

Next to the technological challenges alternative cements phases regulatory and perception issues. For instance, it is believed that contractors and architects – who have to build structures that last for decades – are notoriously conservative and easily take the risk by using alternative types of cement.
Carbonate mineralisation (other)

In this category are included natural forms of carbonate mineralisation, such as weathering. In this process CO₂ is converted to solid carbonates as a result from chemical reactions. When occurring naturally, this is a very slow process. Prior to using this technology for commercial purposes, the reaction speed must be accelerated considerably.

Carbonate mineralisation is a permanent storage option for CO₂. The resulting carbonates can be used e.g. for construction and mine reclamation without the need for monitoring or the concern of potential CO₂ leaks (Parsons Brinckerhoff/GCCSI, 2011).

Current development status
The development of carbonate mineralisation is still in the R&D-phase. Projects are moving from lab-scale towards pilot-scale mineralising hundreds of kilos of CO₂ per hour. The activities on carbonate mineralisation are spread all around the world, mostly depending on the availability of minerals. In Europe, activities are deployed in Finland, the UK and Hungary.

One of the major challenges in the development of the technology is to increase the speed of the process. To become commercially interesting, a scale of Mton CO₂ per hour should be reached. Also more research is needed on CO₂ mineralisation in olivine type of rocks (Zevenhoven et al., 2012). Currently, the possibility to mineralise CO₂ from a 500 MW coal-fired power plant in Finland (Meri-Pori) is being assessed (Zevenhoven et al, 2012). In another project, Finnish researchers are collaborating with researchers from A*Star (Singapore Institute for Chemical Engineering) and to explore the potential uses of the resulting product to enlarge their land area (Abo Akademi, 2011).

Currently, mostly universities are involved in the development of carbonate mineralisation together with some industrial partners. Collaborations between the different stakeholders is getting started. Especially between European universities collaboration is being initiated on writing articles and PhD-theses. Stakeholders note that the involvement of companies is important and should be stimulated, because they want to get rid of the CO₂ and can make the necessary investments.

The products resulting from carbonate mineralisation can be used as building materials. Here it should be noted that there are no significant commercial benefits of the technology and that currently these CCU alternatives are more expensive then conventional building materials. Therefore, the commercialisation of the technology will largely be driven by the environmental benefits (Parsons Brinckerhoff/GCCSI, 2011).

One of the advantages of the technology is that there is a great potential for CO₂ storage available. In the area around a 500MW coal-fired power plant in Meri-Pori (Finland) are enough minerals available to store 40 years of CO₂ emissions (Zevenhoven et al., 2012). There is no exact information on the abatement potential of the global mineral reserves, but according to stakeholders it could have a significant contribution to CO₂ reduction worldwide.
The availability of funds to study carbonate mineralisation is limited. Only Tekes (the Finnish Funding Agency for Technology and Innovation) was identified so far. According to the stakeholders, one of the reasons is that carbonate mineralisation is not fully acknowledged as a research area, withholding specific research calls.

Currently, there is not much known about the public perception of carbonate mineralisation. As the resulting product is in a solid state, stakeholders expect that there will be less opposition as compared to CO₂ in gaseous or liquid form. This could be strengthened by giving it a useful application as building material, which would be appreciated over storing the product.

### Technology summary carbon mineralisation (cement and other products)

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Description</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technology/application</td>
<td>Carbon mineralisation</td>
<td>GCCSI, 2011, Accelerating the uptake of CCS: Industrial use of captured CO₂, Appendix F;</td>
</tr>
<tr>
<td>Brief description</td>
<td>Carbon mineralisation is the conversion of CO₂ 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 CO₂ 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 CO₂ leaks that could pose safety or environmental risks.</td>
<td></td>
</tr>
<tr>
<td>Technology description</td>
<td>In mineral carbonation, alkaline and alkaline-earth oxides such as magnesium oxide (MgO) and calcium oxide (CaO), which are present in naturally occurring silicate rocks such as serpentine and olivine are chemically reacted with CO₂ to produce compounds such as magnesium carbonate (MgCO₃) and calcium carbonate (CaCO₃, commonly known as limestone).</td>
<td>Joe Jones, 2012, Skyonic Corp., Carbon Capture Is As Easy As Turning CO₂ Into Baking Soda, <a href="http://www.epmag.com/Technology/Carbon-Capture-Is-As-Easy-Turning-CO2-Baking-Soda_93905">http://www.epmag.com/Technology/Carbon-Capture-Is-As-Easy-Turning-CO2-Baking-Soda_93905</a></td>
</tr>
<tr>
<td>Technology providers</td>
<td>Calera (USA), Skyonic Corporation (USA), Reichert Power Corporation (USA), Capitol Aggregates Ltd (USA), Polaron (Global), Cambridge Carbon Capture (UK), University of Sheffield (UK), Åbo Akademi University and Helsinki University of Technology (Finland)</td>
<td>GCCSI, 2011, Accelerating the uptake of CCS: Industrial use of captured CO₂, Appendix F; Polaron, 2012, Research collaboration with Cambridge Carbon Capture, <a href="http://polarcos.com/en/us/tech/research-collaboration-with-cambridge-carbon-capture.php">http://polarcos.com/en/us/tech/research-collaboration-with-cambridge-carbon-capture.php</a></td>
</tr>
<tr>
<td>CO₂ sources and requirements</td>
<td>CO₂ can be supplied in roughly three ways: directly from the air; using flue gases or high-concentration through capture. For mineral carbonation dilute CO₂ from flue gas can be used as feedstock.</td>
<td>GCCSI, 2011, Accelerating the uptake of CCS: Industrial use of captured CO₂, Figure 3.3 (page 40);</td>
</tr>
<tr>
<td>CO₂ utilisation rate</td>
<td>8 ton of mineral carbonation and cement formed by the Calera process contains 0.5 ton CO₂. Adsorption of one tonne of carbon dioxide using the Calera process (use of industrial waste (fly ash), and alkalinity source – natural or manufactured) requires almost one tonne of brine or manufactured alkalinity (sodium hydroxide), and part fly ash. Each tonne of mineral carbonisation and cement formed by the Calera mineralisation process contains one-half tonne of CO₂.</td>
<td>GCCSI, 2011, Accelerating the uptake of CCS: Industrial use of captured CO₂, Appendix F;</td>
</tr>
<tr>
<td><strong>TECHNOLOGY STATUS</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-----------------------</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Destination of CO2</strong></td>
<td>Carbonate mineralisation is regarded as method to permanently store CO2. The carbonates produced are stable and will not lead to any significant releases of CO2 over time. It could provide a permanent storage solution for CO2 without the need of (long-term) monitoring.</td>
<td></td>
</tr>
<tr>
<td><strong>Technology and project status</strong></td>
<td>Carbonate mineralisation is currently demonstrated by Calera. At their facility in California they operate a scaled-up pilot plant (natural gas) equivalent to 30MW of coal fired. The materials generated with the CO2 are used in external construction (Calera, 2012).</td>
<td></td>
</tr>
<tr>
<td><strong>Estimated time to commercial deployment</strong></td>
<td>In 2009 mineralisation was considered a niche market and was still in basic R&amp;D. Carbonate mineralisation is at the earliest from 2015 onwards commercially available.</td>
<td></td>
</tr>
<tr>
<td><strong>R&amp;D programmes and objectives</strong></td>
<td>Important to reduce sequestration costs is the heat integration of the capture and fixation process. Current R&amp;D activities in carbonate mineralisation are focused on achieving energy-efficient reactions and reaction rates viable for storage of significant volumes of CO2 from industrial processes by using either: • natural rock silicates; or • industrial waste (fly ash and waste water/brine).</td>
<td></td>
</tr>
<tr>
<td><strong>European initiatives</strong></td>
<td>Åbo Akademi University and Helsinki University of Technology (Finland by Ron Zevenhoven) While most research is concentrating on methods using aqueous solutions, research using a fluidised bed reactor for gas/solid dry carbonation is being conducted in Finland. Although this technology is showing promising results, the process is energy intensive requiring high temperatures and high pressures (600ºC and 100 bar).</td>
<td></td>
</tr>
<tr>
<td><strong>GCCSI, 2011, Accelerating the uptake of CCS: Industrial use of captured CO2</strong>, page 33</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>GCCSI, 2011, Accelerating the uptake of CCS: Industrial use of captured CO2</strong>, Appendix F; GCCSI, 2011, Accelerating the uptake of CCS: Industrial use of captured CO2, Figure 3.3 (page 40); Calera, 2012, Scale up, <a href="http://calera.com/index.php/technology/scale_up/">http://calera.com/index.php/technology/scale_up/</a></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>RWE, 2009, Potential of CO2 utilisation; BMBF CCU seminar 2009</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

ECUNL11593 121
### European projects:

There are large differences in the estimated costs of the various carbonation technologies. According to Hagen (2007), the costs ranges for the most realistic route between 60 to 100 euro/tonne CO2 avoided. The lower costs are associated with processes using waste streams like steel slag as feedstock. For some process which requires high concentration of CO2, the capture costs needs to be added to the aforementioned costs.

Calera plans to build a facility, Calera Yallourn, in the Latrobe Valley, Australia, which following a demonstration phase will be the first commercial scale facility capable of capturing 250MW of CO2. The CO2 will be captured from the fly gas of a local coal power station. Calera have estimated that the costs associated with the facility are as follows:

- **CAPEX** requirement (including CO2 capture and building materials) of US$300-310/MWh CO2 avoided.
- **OPEX** requirement of US$50-60/MWh CO2 avoided.
- A cost of CO2 capture of US$45-60/tonne of CO2.

Details of further operating and maintenance costs are not available.

### Markets

Potential markets for products generated from mineralisation include:

- Mine reclamation.
- Construction materials – aggregate.
- Supplant portion of cement.

The main markets for the use of the carbonates produced via the CMAP process are the cement and aggregates markets as alternatives to traditionally produced Portland cement and building aggregates.

### Cost factors

There are large differences in the estimated costs of the various carbonation technologies. According to Hagen (2007), the costs ranges for the most realistic route between 60 to 100 euro/tonne CO2 avoided. The lower costs are associated with processes using waste streams like steel slag as feedstock. For some process which requires high concentration of CO2, the capture costs needs to be added to the aforementioned costs.

Calera plans to build a facility, Calera Yallourn, in the Latrobe Valley, Australia, which following a demonstration phase will be the first commercial scale facility capable of capturing 250MW of CO2. The CO2 will be captured from the fly gas of a local coal power station. Calera have estimated that the costs associated with the facility are as follows:

- **CAPEX** requirement (including CO2 capture and building materials) of US$300-310/MWh CO2 avoided.
- **OPEX** requirement of US$50-60/MWh CO2 avoided.
- A cost of CO2 capture of US$45-60/tonne of CO2.

Details of further operating and maintenance costs are not available.

### Current and future potential demand

Mineralisation can potentially reuse all fossil CO2 (Geerlings, 2009)

According to Zevenhoven (2009) the worldwide potential capacity for mineralisation is 5 billion ton CO2.

Calera has estimated that the current global demand for building materials is 32 billion tonnes per year and is expected to see year on year growth. According to the International Energy Agency, cement production is projected to grow by 0.8-1.2 per cent per year until 2050.

### Market development factors

Acceptance of products as replacement for existing aggregate and cement supply. The success of the technology is dependent on the market accepting the product and the successful penetration of the market. Calera claim that price competitive products can be produced through the use of the CMAP process. However, this expectation should be treated with caution since the technology is not yet commercial.

### Regional considerations

Currently, most of the development of these processes take place in the US, Australia and Oman. In Europe, not a lot is happening.

Concerning the application of the technology, there are no reasons to assume that there are barriers that block application of the technology in Europe.

### Barriers to widespread deployment

### Technical

The technology is limited by the fraction of silicate reserves that can be technically exploited, and the additional intensive operations of mining, crushing, milling and transporting the mineral-bearing ores to the processing plant for mineralisation. For these reasons commercial silicate mineral carbonation technology does not yet exist.

Other key technical challenges in mineral carbonation are (i) slow kinetics of carbonation of feedstock materials e.g. magnesium and/or calcium silicate rocks; (ii) the logistics and integrated supply chain competencies required for large volumes of feedstock minerals and products with a diversity of industrial point-sources of CO2; (iii) large amounts of material needed: 3 tons per ton CO2 and 8 tons per ton coal (Zevenhoven, 2009).

### DOE funding:

None

### European funding:

None

### Sources of revenue generation

The main products are Portland cement and building aggregates. Calera claim that CMAP (Carbonate Mineralisation by Aqueous Precipitation) products can be made and sold competitively in the current market with estimates that approximately 1.5 billion tonnes of Portland cement could be substituted with carbonate cement, and another 30 billion tonnes of aggregate used in concrete, asphalt, and road base could be substituted.

There is a potential for this technology to produce sustainable revenues through the sale of the carbonate products. However, this is dependent on the market accepting the product and the successful penetration of the market. Calera claim that price competitive products can be produced through the use of the CMAP process. However, this expectation should be treated with caution since the technology is not yet commercial.
## Life-cycle GHG emissions

**Case study:**
PB estimate of requirements based on capture at a brown coal-fired power plant in Victoria, Australia, with no requirement for manufactured alkalinity.

### T CO₂-E EMITTED IN THE ACT OF REUSE OF 1 TONNE OF CO₂:

| CO₂-Emitted | 0.32 |

Significant amounts of energy is required for mining, transport and pre-processing the minerals (e.g. grinding to enhance the reaction speed). This reduces the CO₂ avoidance effectiveness of the process (Styring, 2011). When high-concentration of CO₂ is required, also energy for capturing and transporting the CO₂ is required.

Mineralisation of CO₂ is an endothermic process, i.e. heat is produced during the reaction process. Considerable energy (heat and power) is required for the process leading to additional CO₂ emission and reducing the CO₂ sequestration efficiency. Huijgen (2007) estimates that for aquatic mineralisation process the effectiveness of CO₂ sequestration is reduced to 70% (due to mining, transport, pre-treatment, etc).

### GCCSI, 2011, Accelerating the uptake of CCS: Industrial use of captured CO₂, Table 4.3 (page 47);
Styring, 2011

## Other environmental considerations

### Extensive mining operations are required, which may lead to [local] environmental impacts.

Adoption of one tonne of carbon dioxide using carbonate mineralisation based on natural rock silicates with high pressure and temperature CO₂ in a fluidised bed requires around three tonnes of serpentinite or equivalent ultramafic rock (or 6–7 tonnes of such rocks are required to absorb the carbon dioxide from the combustion of every tonne of coal) (Hunwick, 2009).

To store one tonne of CO₂ as carbonates using wet carbonate mineralisation (based on natural rock silicates and aqueous solutions) requires 2.4 tonne of NaOH and 2-4 tonne of make-up acid (Ron Zevenhoven et al, 2007). ([unclear to me: what is the relevance (costs, environment)]

### Hunwick, 2009, In: GCCSI, 2011, Accelerating the uptake of CCS: Industrial use of captured CO₂, Appendix F;
Zevenhoven et al., 2007, In: GCCSI, 2011, Accelerating the uptake of CCS: Industrial use of captured CO₂, Appendix F;
## Technology summary concrete curing

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Description</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technology/application</td>
<td>CO₂ concrete curing</td>
<td></td>
</tr>
<tr>
<td>Brief description</td>
<td>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 through very weak and gaining in strength in the weeks following.</td>
<td>GCCSI, 2011, Accelerating the uptake of CCS: Industrial use of captured CO₂, Appendix G;</td>
</tr>
<tr>
<td>Technology description</td>
<td>Instead of using traditional energy intensive steam curing methods an alternative method reusing CO₂ can be used. This method, developed by Carbon Sense Solutions, makes use of flue gases from the cement production to cure precast concrete products, while remaining the same quality conditions.</td>
<td>GCCSI, 2011, Accelerating the uptake of CCS: Industrial use of captured CO₂, Appendix G;</td>
</tr>
<tr>
<td>Technology providers</td>
<td>Calera, Carbon Sense Solutions (Canada), McGill University (USA)</td>
<td>GCCSI, 2011, Accelerating the uptake of CCS: Industrial use of captured CO₂, Appendix G;</td>
</tr>
<tr>
<td>CO₂ sources and requirements</td>
<td>Concrete curing requires dilute CO₂ from flue gases. Carbon Sense Solutions (Canada) is seeking to use a point source of CO₂ to limit the need for heat and steam curing of precast concrete products. Instead of the traditional energy intensive steam curing technologies, the Carbon Sense concrete curing process consumes CO₂ from onsite flue gases and local.</td>
<td>GCCSI, 2011, Accelerating the uptake of CCS: Industrial use of captured CO₂, Appendix G; Figure 3.3 (page 40);</td>
</tr>
<tr>
<td>CO₂ utilisation rate</td>
<td>Carbon Sense Solutions has indicated that up to 120kg of CO₂ per tonne of precast concrete is sequestered during the curing process. However, this figure may represent the total CO₂ offset that the technology can deliver.</td>
<td>GCCSI, 2011, Accelerating the uptake of CCS: Industrial use of captured CO₂, Appendix G;</td>
</tr>
<tr>
<td>Destination of CO₂</td>
<td>Concrete curing is regarded as method to permanently store CO₂</td>
<td>GCCSI, 2011, Accelerating the uptake of CCS: Industrial use of captured CO₂, Figure 3.3 (page 40);</td>
</tr>
<tr>
<td>Technology and project status</td>
<td>Carbon Sense Solutions Inc (CSS) is partnering with industry and the government to demonstrate and optimise the concrete curing process utilising CO₂ instead of heat and steam at an industrial scale. Extensive design and industrial testing is underway to minimise the installation and operation risks.</td>
<td>GCCSI, 2011, Accelerating the uptake of CCS: Industrial use of captured CO₂, Appendix G;</td>
</tr>
<tr>
<td>Estimated time to commercial deployment</td>
<td>Currently CSS has funding secured for its first full scale demonstration plant to be implemented in winter 2011. Commercialisation of the technology is planned for 2012.</td>
<td>GCCSI, 2011, Accelerating the uptake of CCS: Industrial use of captured CO₂, Appendix G;</td>
</tr>
<tr>
<td>R&amp;D programmes and objectives</td>
<td>European projects: None</td>
<td>GCCSI, 2011, Accelerating the uptake of CCS: Industrial use of captured CO₂, Appendix G;</td>
</tr>
<tr>
<td></td>
<td>Other projects: McGill University (DOE funded: USD 400k) - In collaboration with 3H Company (Lexington, Ky.), researchers aim to develop a curing process for the precast concrete industry that uses CO₂ as a reactant.</td>
<td>GCCSI, 2011, Accelerating the uptake of CCS: Industrial use of captured CO₂, Appendix G;</td>
</tr>
<tr>
<td>Demonstration projects</td>
<td>European projects: None</td>
<td>GCCSI, 2011, Accelerating the uptake of CCS: Industrial use of captured CO₂, Appendix G;</td>
</tr>
<tr>
<td></td>
<td>Other projects: Carbon Sense Solutions - Carbon Sense Solutions is partnering with Air Liquide, the Shaw Group in Nova Scotia, Canada, and the Government of Nova Scotia to demonstrate and optimise the cost-saving, technological and environmental merits of its Carbon Sense Concrete Curing process.</td>
<td>GCCSI, 2011, Accelerating the uptake of CCS: Industrial use of captured CO₂, Appendix G;</td>
</tr>
<tr>
<td>Funding and support programmes</td>
<td>European projects: None</td>
<td>GCCSI, 2011, Accelerating the uptake of CCS: Industrial use of captured CO₂, Appendix G;</td>
</tr>
<tr>
<td></td>
<td>Other projects: McGill University (DOE funded: USD 400k) - In collaboration with 3H Company (Lexington, Ky.), researchers aim to develop a curing process for the precast concrete industry that uses CO₂ as a reactant.</td>
<td>GCCSI, 2011, Accelerating the uptake of CCS: Industrial use of captured CO₂, Appendix G;</td>
</tr>
</tbody>
</table>
### Sources of revenue generation

An CO2 negative alternative to Portland cement.

Use of CO2 for curing as an alternative to current methods is unlikely to be more profitable since research suggests that concrete cured under this technology will not have a technological advantage over traditional methods and therefore the concrete is unlikely to be able to be sold at a premium. The main economical benefit is derived from any cost savings which can be made through using CO2 as opposed to an alternative; however research suggests that with the current costs of carbon capture, the technology is more costly.

### Cost factors

Currently, CO2 concrete curing is relatively expensive due to the high carbon capture costs. Expectations are that with rising carbon prices, interest in CO2 reuse technologies will grow and costs for capture will decrease. Its competitiveness will largely depend on other advantages, such as reduced curing time and high carbon prices.

### Current and future potential and demand

Precast concrete is widely used in many different building constructions, such as housing, stadiums, pavements, walls, transportation products, etc. In 2009, global concrete production exceeded 10 billion tonnes. Exact numbers for Europe were not found.

### Market development factors

The main driver of this technology is likely to be the price and demand of concrete. A further driver of implementation of the technology will be the existence of a carbon trading scheme and the reduced curing time.

### Regional considerations

Concrete curing has a great change to develop well in Europe. The technology is being developed partly in Europe and the concrete and cement sector are included in ETS. This opens up extra opportunities, especially when the ETS-price will increase.

### Barriers to widespread deployment

Investments: The concrete sector operates within a highly competitive commodity market with limited capital to invest in new technologies. Prices for CO2 capture should be lowered.

### Life-cycle GHG emissions

**Case study:** Utilises a flue gas slipstream from a coal-fired power station in Nova Scotia, Canada, with the precast facility located in close proximity.

**CO2 emitted in the act of reuse of 1 tonne of CO2:** 2.2

Note: The use of anthropogenic CO2 in concrete curing has genuine mitigation potential, with a good CO2 balance expected when compared to a conventional concrete production method. In fact 99 per cent of the CO2 emissions initially listed above for CO2 concrete curing is attributable to the use of cement in the manufacture of concrete, which is an unavoidable component of any concrete production process. The reported result is not an error, merely a consequence of the boundaries assumed for the LCA exercise. Limitations of the life cycle analysis are further discussed below.

### Other environmental considerations

-
Polymer processing

In polymer processing CO₂ can be utilised in combination with traditional feedstock to synthesise polymers. This technology allows the use of CO₂ and transforms it into polycarbonates. Polymers that can be created with this technology are polypropylene carbonate (PPC) and polyethylene carbonate (PEC) (Parsons Brinckerhoff/GCCSI, 2011).

The potential of CO₂ in polymers production was already discovered in the 1970s, but it took until 2009 before a catalyst was developed that reduce the energy significantly for the polymerisation process.

Current development status
Polymers produced with reusing CO₂ is being developed worldwide. Both in Europe and North America several academic institutions and industrial organisations are developing this technology (Parsons Brinckerhoff/GCCSI, 2011). In Europe, most of the activities take place in Germany, where different R&D and pilot projects are being deployed. Two of the largest projects, Dream Production and CO₂rrect, include multiple stakeholders among which University of Aachen, Bayer, RWE, Siemens and BASF. Most of the pilot-scale demonstration projects will be completed in 2013-2014. The next step would be to demonstrate the technology on a medium-size scale and then scale up to a large-scale chemical plant. Preparations for demonstration projects are already ongoing. The Dream Production project is aiming to make the polymers commercially available in the second half of this decade (see also Box 1).

To compete with the incumbent polymers, price competitiveness is very important. This requires improvements in the current production process to cut costs. The focus of the pilots is now on the scalability of the products, bringing the production volume from a multiple litre scale to a ton-scale.

As mentioned above, many different types of stakeholders are involved in the development of these polymers. Besides universities, several large industrial companies are involved in the pilot projects. At this stage, collaborations are numerous and well organised. When the technology enters large-scale demonstrations, it is expected that the collaborations will become more complex, as a result of Intellectual Property Rights.

Besides collaborations, several conferences and workshops are organised specifically for CO₂ reuse in polymers, such as "Carbon dioxide as feedstock for chemistry and polymers"²¹ (Essen) and "The CO₂ challenge forum"²² (Lyon).

According to the stakeholders, the development of polymer processing is going according to plan and is on track. To maintain this pace, ongoing support in the form of funds is important. One of the sponsors of the projects is the German Federal Ministry of Education and Research that has

---

²¹ Conference took place on October 7-9, 2012, website: [http://www.CO2-chemistry.eu/](http://www.CO2-chemistry.eu/)
implemented several R&D programmes to support CO₂ utilisation. One of these programmes is Chemical Processes and Use of CO₂, with a budget of €100 million for 8 years (2009 – 2016) (BMBF, 2012).

The main difference between conventional polymers and their CCU alternatives is that the alternatives are produced in a more sustainable way, using less fossil fuels and materials. This could be an important selling point for these polymers. Furthermore, there are some technological advantages, which are currently being elaborated. On the longer term, the importance of these technologies can increase, as stakeholders expect that CO₂ can become an important resource for the chemical industry in the future. Decreasing oil feedstock and resulting increasing oil prices are expected to become important drivers.

Technology providers expect that CO₂ reuse can be selling point for their products, but they are aware of the public perception around CO₂. Therefore, already in this stage of the development, communication is kept open to make sure that when they become commercially available, the products are accepted. In their communication is explained what they do, how CO₂ reuse works and what the effects are. Stakeholders suggested a European wide communication on the use of CO₂ in production processes to avoid misperception by consumers.
Technology summary polymer production

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Description</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technology/application</td>
<td><strong>Brief description</strong> 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 (Wikipedia, 2012). A new approach to polymer processing is to use CO2 in combination with traditional feedstocks to synthesise polymers. This technology allows the use of waste CO2 and transforms it into polycarbonates. The polymers that can be created with this technology are polypropylene carbonate (PPC) and polyethylene carbonate (PEC) (GCCSI, 2011). The potential of CO2 in polymers production was already discovered in 1968. It took until 2009 before a catalyst was used that would reduce the energy for the polymerisation process, so that it became economic viable.</td>
<td>Wikipedia, 2012, <a href="http://en.wikipedia.org/wiki/Polymer">http://en.wikipedia.org/wiki/Polymer</a>; GCCSI, 2011, Accelerating the uptake of CCS: Industrial use of captured CO2, Appendix D;</td>
</tr>
<tr>
<td>Technology providers</td>
<td><strong>Pilots / demonstration:</strong> Bayer (Germany) BASF (Germany) RWE (Germany) R&amp;D: Coates Group, part of Cornell University (USA) Pilot and demonstrations: Novomer Ltd (USA) Kodak Specialty Chemicals facility in Rochester NY (USA) Praxair (USA) Albemarle Corporation (USA) Eastman Kodak (USA)</td>
<td>Alexis Bazzanella (BMBF), 2012, Research on chemical CO2 utilization in Germany GCCSI, 2011, Accelerating the uptake of CCS: Industrial use of captured CO2, Appendix D;</td>
</tr>
<tr>
<td>CO2 sources and requirements</td>
<td>Polymer processing requires a high concentration of CO2. The CO2 will be generated from point source, such as syngas production, natural gas sweetening and coal fired power plants. The captured CO2 should undergo an additional processing step to increase the purity of the CO2. It is not known how pure the CO2 stream should be or if there are specific requirements for the CO2.</td>
<td>GCCSI, 2011, Accelerating the uptake of CCS: Industrial use of captured CO2,Figure 3.3 (page 40); GCCSI, 2011, Accelerating the uptake of CCS: Industrial use of captured CO2, Appendix D;</td>
</tr>
<tr>
<td>CO2 utilisation rate</td>
<td>Based on the first figures from Novomer, their polymers contain up to 50% CO2 by mass. According to Novomer in 2010, the current market for PP is 45.1 Mt. If PPC could compete with this market, potentially 22.5 Mt CO2 could be re-used annually.</td>
<td>GCCSI, 2011, Accelerating the uptake of CCS: Industrial use of captured CO2,Figure 3.3 (page 40); GCCSI, 2011, Accelerating the uptake of CCS: Industrial use of captured CO2, Appendix D;</td>
</tr>
<tr>
<td>Destination of CO2</td>
<td>Depending on the application for PPC, the permanence of CO2 storage could vary between (almost) permanent to only temporary. For the latter, polycarbonates can be recycled via hydrolysis reactions and is in some cases biodegradable. In ideal compost conditions polycarbonates can degrade in six months.</td>
<td>GCCSI, 2011, Accelerating the uptake of CCS: Industrial use of captured CO2,Figure 3.3 (page 40); GCCSI, 2011, Accelerating the uptake of CCS: Industrial use of captured CO2, Appendix D;</td>
</tr>
</tbody>
</table>
### Technology and project status

The technology is still at a relatively early stage—it has only been demonstrated at a small scale (using a batch reactor). Pilot and demonstration projects of the technology are ongoing since 2009. First commercial applications are expected in 2015.

GCCSI, 2011, Accelerating the uptake of CCS: Industrial use of captured CO2, Appendix D;

### Estimated time to commercial deployment

In 2009 polymers were indicated to be in the phase of pilot plants. It is estimated that it would take 5 years to introduce commercial applications of this technology. It is expected that several products will be customer qualified requiring commercial scale production of PPC polymers on a global basis.

GCCSI, 2011, Accelerating the uptake of CCS: Industrial use of captured CO2, Figure on page XIII;
GCCSI, 2011, Accelerating the uptake of CCS: Industrial use of captured CO2, Appendix D;

### R&D programmes and objectives

**Research:**

- Using CO2 as a polymer feedstock is possible through the use of a zinc-based catalyst system, which reacts CO2 and epoxide molecules via a low energy pathway. Research into the catalyst system was investigated and developed by the Coates group, a part of Cornell University. The catalyst is now the system used by Novomer in their pilot plant. Novomer is involved in a range of development activities, from polymer synthesis to application testing.

GCCSI, 2011, Accelerating the uptake of CCS: Industrial use of captured CO2, Appendix D;
DOE (2010), http://fossil.energy.gov/recovery/projects/beneficial_reuse.html

### Demonstration projects

**European projects:**

- **Dream Reactions (Bayer Technology Services):** Chemical CO2 utilisation; Dream Production (Bayer MaterialScience) using CO2 from coal-fired power plant (RWE): Pilot plant launched Feb 2011; Dream Polymers (Bayer MaterialScience): Sustainable pathways to new polymers; CO2 as polymer building block (BASF); Continuous process for CO2 fixation in polymers (BASF);
- **RWE Power:** Power production with CO2 from coal power plant. The mitigation potential is estimated at 2-3 Mton CO2 per year.

Alexis Bazzanella (BMBF), 2012, Research on chemical CO2 utilization in Germany
RWE, 2009, Potential of CO2 utilisation, BMBF CCU seminar 2009
DOE (2010), http://fossil.energy.gov/recovery/projects/beneficial_reuse.html

### Funding and support programmes

**European funding:**

- **German funding programme:** Technologies for Sustainability and Climate Protection – Chemical Processes and Use of CO2
- Budget: 100M€ (2010 - 2015)

Assisting Novomer to develop its polymer for commercial production, the following grants have gone into funding the above activities:

- Department of Energy USD 2.6 million grant to demonstrate the innovative reuse of CO2: DOE also rewarded Novomer a grant (DOE share USD 18.4 million) to develop applications for polycarbonates.
- New York State Energy Research & Development (NYSERDA) USD 475,000 for two phases of work, including a feasibility study and commercialization activities for the coatings and packaging markets.
- National Science Foundation USD 400,000 to develop a continuous flow manufacturing process to make CO2-based polymers.

Alexis Bazzanella (BMBF), 2012, Research on chemical CO2 utilization in Germany
GCCSI, 2011, Accelerating the uptake of CCS: Industrial use of captured CO2, Appendix D;
DOE (2010), http://fossil.energy.gov/recovery/projects/beneficial_reuse.html
Sources of revenue generation
Polymers created in part from CO2 could replace traditional petroleum based plastics such as polypropylene, polyethylene and polystyrene and polyvinyl chloride if the properties of PPC remain the same for application in a wide range of areas traditional plastics are employed.

Potential markets where PPC could be used:
- Enhanced oil recovery: PPC surfactants can be pumped into oil reservoirs with supercritical CO2. The surfactants improve the solubility of CO2 increasing oil recovery and creating permanent storage for the CO2 within the surfactants.
- Coatings: PPC polyols can be used for a wide variety of coating purposes including: protective finishes for wood and metal in industrial and automotive applications, furniture, flooring and appliance coatings in domestic products and metal can linings for food products.
- Packaging: PPC display many of the properties thermoplastics do, including stiffness, impact resistance, and oxygen barrier protection, allowing for use in the food and general packaging applications. They can be also formed into a variety of forms using common manufacturing processes, such as:
  - Laminates
  - Injection Moulding
  - Extrusion – Film and Sheet
  - Blow Moulding

Cost factors
No information

Current and future potential demand

Novomer claims that the potential revenue generation is high if the polycarbonate plastics can be (a) accepted as a suitable alternative to existing petroleum based plastics and (b) sold at a competitive price. A small share of the existing polymer market could potentially provide stable returns.

The global markets for polyethylene and polypropylene were approximately 80mt and 45mt respectively, representing the two largest polymer markets. The polymer market is expected to see a stable growth of 6 per cent until 2015.

Market development factors

At present, there are no stand-out commercial benefits for this technology, as it is unlikely that the polycarbonate products will be superior to those already existing in the plastics market, nor is it likely that they can be produced and sold at a lower price. Therefore, it is unlikely that consumers will choose the polycarbonate polymers over the existing petroleum based products.

Although Novomer claim that the technology can be used by existing polymer manufacturers it is doubtful that they will invest in the technology infrastructure without a significant identified economic benefit.

Regional considerations

The source of CO2 and the purity required could mean additional polishing at the point of source is required, increasing cost.

Barriers to widespread deployment

Technical:
- CO2 mitigation via increase in efficiency of production process
- CO2-mitigation by embedding captured carbon dioxide (e.g. from coal power plants) and substitution of fossil based carbon (e.g. from oil)

Commercial:
The main market target is the packaging industry which is a low end application so acceptance will be entirely driven by cost. PPC will have to compete with traditional polymers on a cost basis to win market share, otherwise it will be left to high end niche applications such as medical devices.

Although Novomer claim that the technology can be used by existing polymer manufacturers it is doubtful that they will invest in the technology infrastructure without a significant identified economic benefit.

Life-cycle GHG emissions

Case study:
Capture from a coal-fired power station in the USA, delivered via a 9km pipeline to the polypropylene carbonate production facility.

T CO2-E EMITTED IN THE ACT OF RELIEF OF 1 TONNE OF CO2: 5.52

Other environmental considerations

GCCSI, 2011, Accelerating the uptake of CCS: Industrial use of captured CO2, Appendix D;
Annex D – Communication and CO₂ reuse workshop

This study is focused on the stimulation of CCU technologies and to create insights in possible implications on existing European Climate Action policies. The outcomes of the study will influence the development of the CCU technologies on the short to medium term. The European Commission also wishes to build a strategy that impacts CCU in Europe on the long term.

To create a long term strategy, the following aspects are important:

- Raising awareness
- Communication
- Establishing networks
- Building coalitions

There are different ways of addressing these aspects. This report is for instance a good way to reach out to policy makers at the European Commission and raise awareness for CCU technologies. Other CCU stakeholders can also benefit from this report, as long as it will be available for them. Therefore, it is important to invest in communication towards CCU stakeholders and to share our thoughts and conclusions with them. This has resulted in the development of a website (www.CO₂reuse.eu) and the organisation of a workshop. The function of the website is to communicate the key findings of our study and to offer a portal for CCU technologies in Europe. The workshop will serve primarily for presenting and discussing the results of this study, but also to create a platform for stakeholders to bring together key stakeholders.

The progress on the website and the workshop are described in the next sections.

Website

For the development and deployment of current and novel technologies using CO₂, it is important that the information gathered and produced during this project should be made easily accessible to all stakeholders and other interested parties. One good way to do this is through a dedicated website. The main requirements of such a website are that it is well-structured, easily found through internet browsing and where the reuse option is placed in a broader (CCS) context. In this section we describe the set-up and use of the website.

For the purpose of this project, the project team has claimed the domain name of www.CO₂reuse.eu and will use this for the website. This website will function as a knowledge portal during the project to:

- inform stakeholders and interested organisations;
disseminate the results of the study and report the project’s progress; and

promote and announce the workshop

The website consists of different web pages, including a webpage on the project and the workshop. The website functions also as knowledge portal, by providing basic information of CCU technologies and providing information on CCU activities in Europe. Visitors of the website have the opportunity to inform us about reuse initiatives they are aware of. We will place relevant initiatives on the reuse website.

Via the menu-item “contact” people can inform us about CCU initiatives, asking questions about the project and register for the workshop.

Currently the website is online and up-to-date and will be updated regularly. Improvements that are planned are adding presentations (e.g. the presentations held on the 29 May workshop) and improve the lay-out (i.e. adding pictures, etc.)

Figure 7 – Screenshot homepage www.CO2reuse.eu
The website will be maintained by the project team for the duration of the project. One of the possibilities to keep the website online is that it will be hosted by IEA GHG after the project ends.

Workshop

An important aspect of supporting CCU into the future is the communication of the findings of the research in order to facilitate the emergence of stronger research networks and collaboration in the field. The communication and networking should connect different communities with a direct role to play in CCU, such as the energy and chemicals industry, but also industry and policy makers. To facilitate networking, the project team organised a workshop on CCU technologies for participants across the EU, which was held on 24 October 2012 at the Brussels Museum for Natural Sciences.

The workshop was broadly divided in two parts, the first covered presentations from relevant experts who described the current status of CCU technologies from within their field of expertise and the second comprised of discussion panels on "policy and regulation" and "R&D and innovation needs" for CCU. A complete overview of the programme is included in this Annex.

Over 50 participants participated in the workshop, representing a wide variety of organisations. An overview of the participants can be found at the CCU website: http://www.CO2reuse.eu/participants-workshop.html

The workshop was divided in three technical sessions followed by two panel discussions. For each session an outline is prepared of the objective of the session, speakers and topic. This is followed by an overview of the main topics raised during the session and conclusions / recommendations for further work.

Technical sessions with sector experts

Sessions 1 and 2: Overview on CCU and reuse in focus
The topics of the first two workshop sessions are very much related and therefore is decided to combine the two sessions in this summary report. The objective of the first session was to present an overview of the various CCU technologies, their current development status and potential. In the second session two specific cases were described more profoundly: the case of chemicals and the case of minerals.

The two sessions included the following presentations:

During the presentation and the adjacent Q&A sessions the following several topics were described and discussed. The main topics are listed below:

• **CCU technologies have economic potential**
  o CO₂ could be a sustainable alternative to fossil fuels in the chemical sector.
  o Stimulation of innovative uses of CO₂ could eventually lead to the establishment of a CO₂ economy.

• **Collaboration will accelerate the development of technologies.**
  o Combined research will lead to much more than the sum of individual projects.
  o Two of the large German programmes to develop polymer processing are good examples of this. DREAM production and CO₂RRECT are among the most prominent and largest CCU projects in Europe.

• **The development of CCU technologies faces obstacles and challenges.**
  o The development of catalysts to enhance CCU forms a major challenge.
  o Increasing the visibility of products based on CCU is needed to stimulate the public acceptance.
  o Insight in CO₂ emission reductions resulting from using CCU technologies is needed.

**Conclusions / recommendations for further work**

CCU technologies have economic potential and could lead to the development of a CO₂ economy. Currently, we are at starting phase of these developments and we need increasing efforts to develop these technologies.

Based on the presentations and discussions, the following suggestions for further work are made:

• Introduce CCU labelling on products to enlarge the visibility of CCU in products. Established schemes such as the Blau Engel and EC Ecolabel might be very useful.
• Perform LCAs for different CCU technologies to obtain insights in the actual CO₂ reductions of different CCU options.

**Session 3: R&D and policy needs**
The objective of the third session was to obtain insights in the R&D and policy needs in the development of CCU technologies. Three presentations were held, each focusing on different aspects...
and taken from a different perspective: “Horizon 2020” the EU Framework Programme for Research and Innovation, the German government and the EU industry.

The following presentations were included in this session:


During the presentation and the adjacent Q&A sessions several topics were described and discussed. The main topics are listed below:

- **Several R&D stimulation measures for CCU technologies have been implemented**
  - Development of CCU technologies is eligible for funding under the Horizon 2020 EU Framework Programme for Research and Innovation.
  - Germany is actively exploring and developing CCU technologies. The German federal ministry BMBF has set up two programmes: framework programme “Research for sustainable development” (€2.6 billion) and “Energy research programme” (€3.5 billion).
  - In the chemical industry different initiatives to stimulate the development of CCU technologies are being developed, among which SPIRE\(^\text{23}\), a public-private partnership dedicated to innovation in resource and energy efficiency in the process industries.

- **CCU technologies will become beneficial and offer solutions for current and emerging problems.**
  - Energy storage is one of the major challenges in the transition towards renewable energy. CCU technologies offer opportunities for energy storage, such as the production (renewable) methanol. The German ministry BMBF has a specific focus on CCU technologies for energy storage.
  - The chemical industry faces different challenges, among which CO\(_2\) reduction and scarcity of raw materials are two prominent ones. Both open up possibilities for the use CO\(_2\) as a raw material.
  - Although CCU is expensive, it might become profitable in the future, and this prospect – coupled to resistance to CCS *per se* - is driving interest in Germany.

**Conclusions**

\(^{23}\) SPIRE: Sustainable Process Industry through Resources and Energy Efficiency. CEFIC and other European industries are partners in this initiative. More information on SPIRE can be found at: [Link](http://www.spire2030.eu/)
CCU technologies offer potential solutions for current and emerging problems. To stimulate their development, projects are supported under several R&D stimulation programmes.

Panel discussion

Panel discussion 1: Policy and regulation
Panel: Michael Carus (NOVA Institute), Gernot Klotz (CEFIC) and Ludo Diels (VITO)
Moderator: Paul Zakkour

The objective of the first panel discussion was to discuss issues, barriers and gaps in the existing policy and regulatory frameworks applicable to CCU in the EU. Central questions in this session were: what are the influences of the current policy framework in the development of CCU technologies? How can CCU benefit from policies and regulations? What can be the role of the European Commission?

The following topics have been discussed during the panel discussion:

- **Implementation of CCU technologies under current European policy framework.**
  - It was noted that the current political framework might not be sufficient to foster CCU technologies. As an example was mentioned that adjustments to the Renewable Energy Directive (RED) are needed to fully implement CO₂ fuels.
  - Embedding of CCU technologies in the policy framework is needed to create an incentive for investments in technological development.

- **Stimulation of technological development requires careful considerations on the use of policies and regulation.**
  - Technological development does not always imply that more money should be invested. It is more complicated than that. Technological development is for instance also about coordination of efforts and daring to invest.
  - It is important to build a good business case around CCU technologies, rather than creating favourable market circumstances.
  - Still, additional research is needed to make the CCU alternative cost-competitive with existing products.

- **Embedding CCU technologies in policies and regulations should take place on different levels**
  - Stimulation of CCU should not be limited to the European level only, but should also take place at the Member State level.
  - National regulations are needed to provide the right environment for investments.

Conclusions / recommendations for further work
The panel made several suggestions for the role of policies and regulations in the development of CCU technologies. Different topics and issues were raised and discussed, but unfortunately not always in detail. Therefore, it is hard to distil specific ideas or suggestions from the panel discussion.
Nevertheless, the discussion topics give a good insight in what is currently important in the development of these technologies.

Topics that need further research:

- Analyse of the influence of the current policy framework on the development of CCU technologies.
- Identify the weak spots in the development of CCU and define specific actions to stimulate the development.

Panel discussion 2: R&D and innovation needs

Panel: Lothar Mennicken (BMBF), Vassilios Kougionas (DG RTD), Christopher Gürtler (Bayer) and Michael North (University of Newcastle)
Moderator: Torsten Wöllert (DG CLIMA)

The objective of the second panel discussion is to identify current needs to improve and accelerate R&D and innovation. Specific questions that were used to shape the discussion were: what are the current challenges? What can be the role of collaboration? How should collaboration be organised?

The following topics have been discussed during the panel discussion:

- **Bridging “the Valley of Death” should get focused attention.**
  - To stimulate the development of the technologies and to bridge “the Valley of Death” more collaboration between stakeholders, projects and Member States is needed.
  - Europe should go forward and initiate demonstration projects. European funding programmes such as Horizon 2020 offer good opportunities to facilitate this.
  - The close relation of CCU to renewable energy makes it more difficult to get good cost estimations for the technologies. This might weaken their business cases.
  - The current ETS-price is too low to create an incentive for developing low-carbon technologies.

- **There are concerns that becoming a world leader in this field is more difficult once other regions are going to invest heavily.**
  - CCU technologies provide Europe with a unique chance to gain a competitive edge. CCU is potentially a global market in which Europe can take the lead.

- **Collaborations need to be shaped to work most efficiently.**
  - There was no consensus in the panel on collaborations should take shape. During the session different forms were discussed, such as large European partnerships, collaboration under Horizon 2020 or on Member State level.
  - It was suggested to establish a representative organisation for CCU technologies. According to the panel such an organisation could be very useful, as long as the focus remains on making progress and keeping the pace of development going. For instance, it opens up possibilities to include CO₂ emitters and potential CO₂ suppliers.
Conclusions / suggestions for further research

The issues raised during this panel discussion are mostly linking in to “the Valley of Death” discussion. Bridging this is not specific to the development of CCU technologies this is always a recurring obstacle. Collaboration between different stakeholders and Member States was perceived to be a good step in accelerating the development. As described above, there was no consensus on how the collaboration should be coordinated.

Topics that need further research:
- Obtain insights in the needs of stakeholders to collaborate most efficiently. This can provide useful information on shaping collaborations.
- Identify the needs for a representative organisation for CCU technologies and what role such organisation could take.

Results and conclusions

The CO₂ reuse workshop brought together a variety of stakeholders all working on different CCU technologies in different sectors and from different perspectives. The participants represented different organisations, such as universities, research institutes, industries, governments and companies, all with a similar purpose: stimulating the development of CCU technologies.

The variety in backgrounds and perspectives lead to a diverse series of topics treated in presentations and resulted in lively discussions.

The main findings of the CO₂ reuse workshop are:
- There is interest in the development of CCU technologies among a wide variety of stakeholders.
- There is a good appetite for putting in efforts in this development.
- Workshops or conferences are good platforms for initiating interaction between stakeholders and could provide a starting point for future collaborations.
- Several topics were raised and discussed, but there is only a small level of detail in the discussions. This impedes the formulation of concrete actions.
- We are still at the beginning of the development pathway and more work needs to be done.
## Workshop programme

**Agenda workshop CO₂ reuse October 24, 2012 - Brussels**

<table>
<thead>
<tr>
<th>Time</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>9:30</td>
<td>Coffee / Tea</td>
</tr>
<tr>
<td>10:00</td>
<td>Welcome</td>
</tr>
<tr>
<td>10:00-10:15</td>
<td>Welcome, introducing the day</td>
</tr>
<tr>
<td>10:10</td>
<td>Welcome address DG Climate Action</td>
</tr>
<tr>
<td>10:15</td>
<td>Overview on CO₂ reuse</td>
</tr>
<tr>
<td>10:15-10:45</td>
<td>The relevance of CO₂ reuse</td>
</tr>
<tr>
<td>10:30</td>
<td>Overview CO₂ reuse</td>
</tr>
<tr>
<td>10:45</td>
<td>Reuse in Focus</td>
</tr>
<tr>
<td>10:45-11:35</td>
<td>The case of chemicals: technical aspects</td>
</tr>
<tr>
<td>11:00</td>
<td>The case of chemicals: R&amp;D needs for innovation; policy and regulation</td>
</tr>
<tr>
<td>11:15</td>
<td>The case of minerals</td>
</tr>
<tr>
<td>11:35</td>
<td>R&amp;D needs and policy session</td>
</tr>
<tr>
<td>11:35-14:00</td>
<td>Introduction to Horizon2020</td>
</tr>
<tr>
<td>12:00</td>
<td>Questions and Discussion</td>
</tr>
<tr>
<td>12:20</td>
<td>Lunch</td>
</tr>
<tr>
<td>12:20-13:20</td>
<td>R&amp;D needs and policy session (continued)</td>
</tr>
<tr>
<td>13:20</td>
<td>Country’s view: the case of Germany</td>
</tr>
<tr>
<td>13:40</td>
<td>Stakeholders perspective on policy and regulation for market introduction of CO₂ reuse products</td>
</tr>
<tr>
<td>14:00</td>
<td>Panel discussions</td>
</tr>
<tr>
<td>14:00</td>
<td>Introduction</td>
</tr>
<tr>
<td>14:20</td>
<td>Panel discussion 1: Policy and regulation</td>
</tr>
<tr>
<td>15:00</td>
<td>Coffee/tea</td>
</tr>
<tr>
<td>15:30</td>
<td>Panel discussion 2: R&amp;D and innovation needs</td>
</tr>
<tr>
<td>16:10</td>
<td>Reporting and wrap up</td>
</tr>
<tr>
<td>16:20</td>
<td>Refreshments and networking</td>
</tr>
</tbody>
</table>

**Speakers:**
- EC and Project team
- Mr. Delgado Rosa – Director
- Chris Hendriks (Ecofys)
- Michael Carus (Nova Institute)
- Michael North (Un. of Newcastle)
- Christopher Gürtler (Bayer)
- Ludo Schyvinck (IMA)
- Vassilios Kougionas (DG RTD)
- Lothar Mennicken (BMBF)
- Gernot Klotz (CEFIC)
- Moderator: Paul Zakkour
- Moderator: Torsten Wöllert
- Moderators + project team

**Notes:**
- ECUNL11593
- 141
Annex E – Overview CO₂ reuse activities

In Europe several initiatives have been started to develop CO₂ reuse technologies. Information on conferences and activities related to CO₂ reuse activities can be found following the links below. Also a selection of reports and networks on CO₂ reuse activities is included. The list can also be found at: http://www.CO2-reuse.eu/CO2-reuse-activities.html

New Journal to be launched by Elsevier in 2013: JOURNAL OF CO₂ UTILIZATION
The Journal of CO₂ Utilization offers a single, multi-disciplinary, scholarly platform for the exchange of novel research in the field of CO₂ re-use for scientists and engineers in chemicals, fuels and materials. To receive updates about this new journal and find out when online submissions will be open, please send an email to energyjournals@elsevier.com with Journal of CO₂ Utilization in the subject line.

Conferences and workshops related to CO₂ reuse

Conference on CO₂ as feedstock
The Nova Institute in Essen organises regularly conferences on carbon dioxide as feedstock. The second conference “on CO₂ as Feedstock for Chemistry and Polymers” will take place from 7 to 9 October 2013, Haus der Technik, Essen, Germany. More information on the conference: http://www.CO2-chemistry.eu/home

European CO₂ reuse initiatives

France
• Algomics, Omics of energy conversion and storage by micro-algae: http://www-heliobiotec.cea.fr/algomics-en.html
• Symbiose, Development of an integrated system to produce methane using a source of industrial CO₂, a source of organic waste, and solar energy: http://anr-symbiose.org/?g=en/node/83
• Shamash, producing bio fuels from autotrophic microalgae: http://www-sop.inria.fr/comore/shamash/wwweng/engindex.html

Germany
• Dream Production, A pilot plant at Chempark Leverkusen, for producing plastics from carbon dioxide (CO₂): http://www.chemicals-technology.com/projects/bayer-CO2-plastics
• WACKER, New catalysts for the hydrogenation of CO₂ to methane for energy storage
• KIT, Storage of electrical energy from regenerative sources in the gas infrastructure: H2O electrolysis and synthesis of gas components
• Photocatalytic CO₂ activation to fuels and base chemicals, TU München
• Development of active and selective heterogeneous photocatalysts for the reduction of CO₂ to C1 base chemicals, University Bochum: http://kongress.achema.de/Beitragseinreichung/Congress+Planner/Datei_handler-tagung-559-file-5668-p-44.html;
• Integrated Dimethylether synthesis based on methane from CO₂, BASF
• Acrylic acid from CO₂ and Ethylene, BASF
• CO₂ based acetone fermentation, Evonik
• Energy-efficient synthesis of aliphatic aldehydes from alcanes and CO₂, Evonik
• Orgkokat – New organocatalysts and catalytic processes for the utilisation of CO₂ as building block for chemical syntheses , Leibnitz-Institute for Catalysis
• Solar-thermochemical synthesis of chemical products from H2O and CO₂, BASF: http://www.basf.com/group/corporate/site-ludwigshafen/AppData/news-and-media-relations/news-releases/P-10-221
• HyCats- New catalysts and technologies for the solar-chemical hydrogen production, H.C. Stark
• Synthesis of fuels from CO₂ and water using regenerative energy, SunFire: http://www.sunfire.de/en/kreislauf/power-to-liquids
• Photocatalytic CO₂ activation to fuels and base chemicals, TU München

CO₂ reuse networks
• CO₂NET, Scientific coordination of CCU activities in Germany (under BMBF); http://www.chemieundCO₂.de/en/160.php
• CO₂Chem Network (UK). A collaboration between a range of UK universities with interest and research programmes looking at ways to utilise CO₂, including CO₂ captured from anthropogenic sources; http://CO₂chem.co.uk

CO₂ reuse reports
• Centre for low carbon futures (University of Sheffield), Carbon Capture and Utilisation in the green economy: http://www.policyinnovations.org/ideas/policy_library/data/01612/_res/id=sa_File1/CCU.pdf