GLOBAL CCS INSTITUTE

PARSONS BRINCKERHOFF

ACCELERATING THE UPTAKE OF CCS: INDUSTRIAL USE OF CAPTURED CARBON DIOXIDE

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Disclaimer

Acknowledgements

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GLOSSARY

%wt	Percentage weight
ABLE	Alkalinity based on low energy
ASTM	American Society for Testing and Materials
AU$	Australian dollars
bbl	Barrel
bn	Billion
$CaCO_3$	Calcium carbonate
CaO	Calcium oxide
CAPEX	Capital expenditure
CARMA	Carbon monitoring for action
CCGT	Combined cycle gas turbine
CCS	Carbon capture and storage
CCUS	Carbon capture, use and storage
CDM	Clean Development Mechanism
CEH	Chemical Economics Handbook
CER	Certified emissions reductions credits
CMAP	Carbonate mineralisation by aqueous precipitation
CO	Carbon monoxide
CO_2	Carbon dioxide
CR5	Counter rotating ring receiver reactor recuperator
CSA	Canadian Standards Association
DOE	Department of Energy (United States)
ECBM	Enhanced coal bed methane
EGS	Enhanced geothermal systems
EJ	Exa joule
EOR	Enhanced oil recovery
ETS	Emission trading scheme
EU ETS	European Union Emission's Trading Scheme
EUR	Euro (currency)
G8	The Group of Eight (Forum of senior officials from eight member states: France, Germany, Italy, Japan, United Kingdom, United States of America, Canada and Russia)
GHG	Greenhouse gas

Gtpa	Gigatonne per annum
GW	Gigawatt
GWe	Gigawatt electrical
H_2	Hydrogen
H_2O	Water
ha	Hectare
HCOOH	Formic acid
HDR	Hot dry rocks
HFR	Hot fractured rocks
IEA	International Energy Association
IGCC	Integrated gasification combined cycle (power plant)
in	Inch
IPCC	Intergovernmental Panel on Climate Change
K	Potassium
kg	Kilogram
km	Kilometre
lb	Pound
LCA	Life cycle assessment
m	Metre
$MgCO_3$	Magnesium carbonate
MgO	Magnesium oxide
MIT	Massachusetts Institute of Technology
mm	Millimetre
MEF	Major Economies Forum
MMP	Minimum miscibility pressure
MMV	Monitoring, measurement and verification
MPa	Mega pascals
Mt	Million tonnes
Mt/y	Million tonnes per year
Mtoe	Million tonne of oil equivalent
Mtpa	Million tonnes per annum
MW	Megawatt
MWe	Megawatt electrical
MWh	Mega watt hour

N	Nitrogen
NaOH	Sodium hydroxide
NETL	National Energy Technology Laboratory
NOAK	Nth of a kind
NPK	Nitrogen-phosphorus-potassium (fertiliser)
NRC-IRAP	National Research Council of Canada Industrial Research Assistance Program
NY	New York
NZ	New Zealand
ºC	Degrees Celsius
OCAP	Organic carbon dioxide for assimilation of plants
OECD	Organisation for Economic Co-operation and Development
OPEX	Operational expenditure
P	Phosphorus
pa	per annum
PB	Parsons Brinckerhoff
PBR	Photo-bioreactor
pH	Measure of acidity
psig	Pounds per square inch gauge
R&D	Research and development
$SCCO_2$	Supercritical carbon dioxide
SCM	Supplementary Cementitious Material
t	tonne
t/d	tonnes per day
t/t	tonne/tonne
TAP	Technology Action Plan
tCO_2	tonnes of carbon dioxide
TiO_2	Titanium dioxide
tpa	tonnes per annum
tpd	tonnes per day
UAN	Urea-ammonium nitrate
US	United States
USA	United States of America
US$	United States dollar – Monetary values are in US$ unless otherwise stated

EXECUTIVE SUMMARY

PURPOSE AND CONTEXT

The fundamental purpose of this report is to investigate existing and emerging uses of CO_2 and to review the potential to capture and reuse CO_2 for industrial applications in order to accelerate the development and commercial deployment of CCS. It considers both the near-term application of mature technologies such as enhanced oil recovery (EOR) and the longer term application of a number of promising new technologies that are still in the initial stages of their technical development.

The global CO_2 reuse market currently amounts to approximately 80 million tonnes/year, and is dominated by EOR demand in North America. EOR accounts for approximately 50 million tonnes of demand annually, of which around 40 million tonnes is supplied annually from naturally occurring CO_2 reservoirs at prices generally in the order of US$15–19/tonne.

The potential supply of anthropogenic CO_2 is very much larger than potential demand. It is estimated that globally around 500 million tonnes of low-cost (<US$20/tonne) high concentration CO_2 is available annually as a by-product from natural gas processing, fertiliser plants and some other industrial sources. At a much higher cost (US$50–100/tonne), around 18,000 million tonnes could also be captured annually from the dilute CO_2 streams currently emitted by power, steel and cement plants.

CO_2 reuse for EOR has been a source of revenue for existing CCS projects in North America, and is incorporated into the planning of many proposed North American CCS projects. Elsewhere in the world, particularly in emerging and developing economies, the potential of EOR as an economic catalyst for CCS development is also being examined. The key question addressed by this report is whether and to what extent EOR and other CO_2 reuse technologies can accelerate the uptake and commercial deployment of CCS.

The future supply and market price of concentrated CO_2 for reuse will be materially affected by the extent to which governments adopt regimes to restrict or penalise CO_2 emissions. Consequently, this report considers the potential for CO_2 reuse to accelerate CCS development under circumstances of both weak carbon restrictions and prices and strong carbon restrictions and prices and their interaction with both low-cost and high-cost capture of CO_2.

KEY CONCLUSIONS

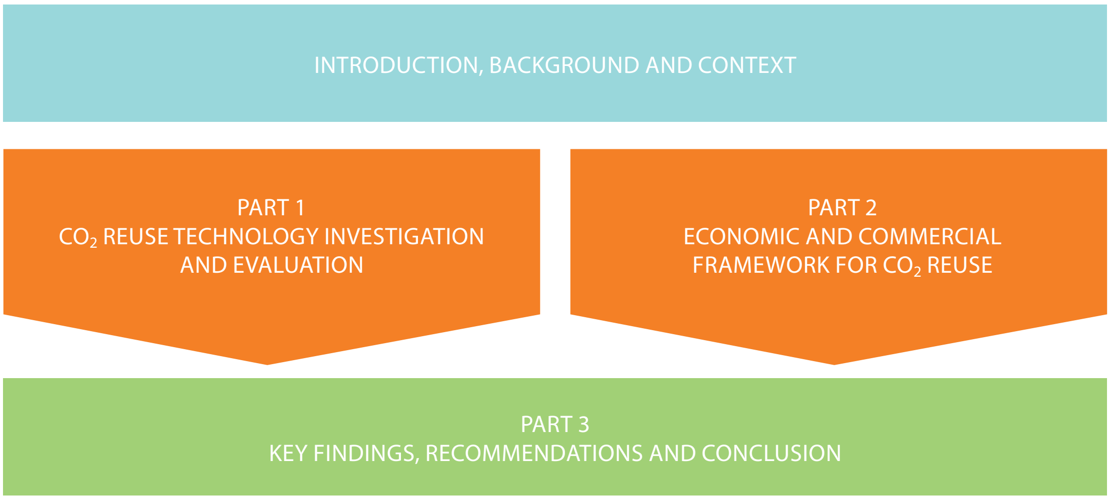
The report's main conclusions are:

1. The current and potential future demand for CO_2 reuse is only a few per cent of anthropogenic CO_2 emissions, and while reuse does not have material global CO_2 abatement potential it has the potential to provide a moderate revenue stream for near-term CCS project development in favourable locations where reuse applications and markets are close to the emission source.
2. EOR will remain the dominant form of CO_2 reuse in the short to medium term due to its maturity and large-scale utilisation of CO_2. As a result it has a role to play in supporting the near-term development of large-scale CCS demonstration projects in regions of EOR potential and in the absence of strong carbon pricing. This initial phase of large-scale CCS demonstration is an essential pre-requisite to commercial deployment, and is critical to the establishment of practical legal and regulatory regimes, to community acceptance and to CCS project optimisation and cost reduction.

3. Most of the emerging reuse technologies still have years of development ahead before they reach the technical maturity required for deployment at commercial scale. Mineralisation technologies may ultimately provide a complementary form of CCS to geological storage, and can facilitate abatement of a small proportion of anthropogenic CO_2 emissions. Technologies that reuse CO_2 in fuel production may also provide indirect mitigation through replacement of fossil fuels. While these are useful attributes, in the near-term they cannot provide a driver to accelerate the commercial deployment of CCS due to their lengthy development timeframes.
4. CO_2 reuse has the potential to be a key component of large-scale CCS demonstration projects in emerging and developing economies, where there is strong demand for energy and construction materials and less likelihood of the early adoption of carbon pricing. The main focus will be on EOR due to its maturity, and potential CO_2 utilisation capacity. Carbonate mineralisation, CO_2 concrete curing, bauxite residue carbonation, enhanced coal bed methane (ECBM), urea yield boosting and renewable methanol may also be of interest in emerging economies such as China and India. However, as noted in point 3 above, some of these technologies are still in the early stages of development and may not be at the required maturity for deployment at commercial scale to coincide with CCS development timeframes.
5. The current market price (US$15–19/tonne) for bulk CO_2 is indicative of the upper limit of prices that can be expected in the future. There is little prospect of a general long-term strengthening of the current bulk CO_2 market price for reuse, and there is every prospect of downward pressure on market prices as and when restrictions on CO_2 emissions are introduced. The revenue generated from reuse will be inadequate to drive the development of CCS for power, steel and cement plants, all of which will require a strong carbon price and/or project-specific funding. CO_2 supply from low-cost sources, such as natural gas processing and fertiliser production, is likely to dominate any reuse supply growth in the medium term.
6. CO_2 reuse has an initial role to play in supporting the demonstration phase of CCS development in the absence of strong carbon prices and in emerging economies. However that initial role, centred on EOR (due to its maturity), becomes less important as and when the cost of emitting carbon rises, which must ultimately happen to facilitate the widespread-commercial deployment of CCS. Furthermore, as noted in point five above, the likelihood is that the market price for bulk CO_2 will fall as carbon prices rise with tightening restrictions on emissions.

REPORT STRUCTURE

This report is structured as follows:



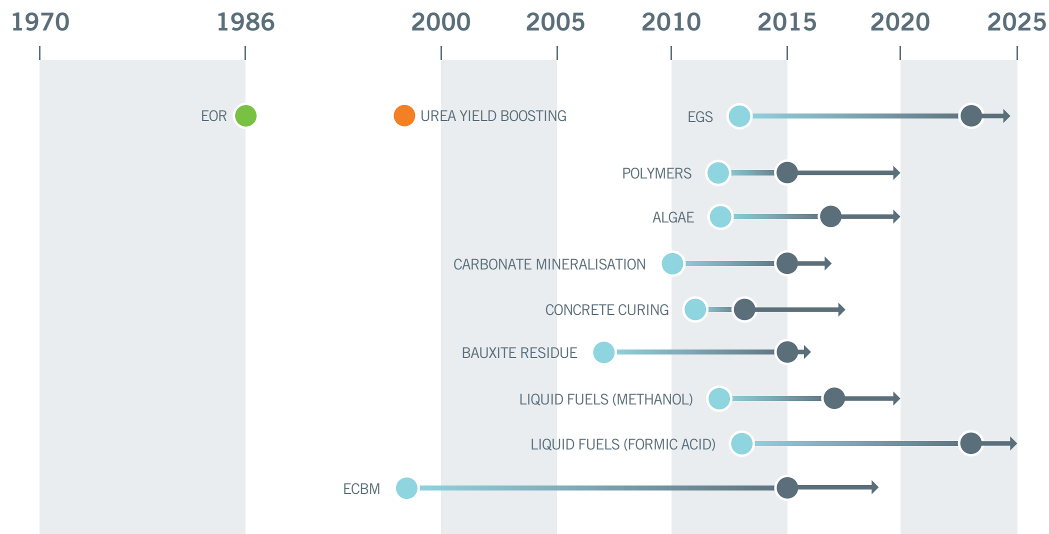
CO_2 REUSE TECHNOLOGIES

Part 1 of this report investigates existing and emerging CO_2 reuse technologies and considers their current and future potential market size. The technologies are short-listed based on the application of a threshold of 5Mtpa of global CO_2 reuse potential. This threshold focuses the study on technologies which are likely to demand CO_2 on a scale commensurate with the emissions generated from power plants and other large industrial point sources, a key to their ability to contribute in some form to accelerating CCS. The CO_2 reuse technologies short-listed for further analysis and evaluation include:

- CO_2 for use in enhanced oil recovery (EOR);
- Mineralisation (including carbonate mineralisation / concrete curing / bauxite residue processing);
- CO_2 as a feedstock in urea yield boosting;
- Enhanced geothermal systems (using CO_2 as a working fluid);
- CO_2 as a feedstock in polymer processing;
- Algae production;
- Liquid fuels (including renewable methanol / formic acid); and
- CO_2 for use in enhanced coal bed methane (ECBM) recovery.

The desktop study of the short-listed technologies above provided an understanding of the characteristics of each technology and highlighted the following:

- The reuse technologies utilise varying sources of CO_2 (from a concentrated stream of CO_2 to a dilute stream of CO_2, such as untreated flue gas) and have varying abilities to permanently store CO_2. These differences lead to varying impacts when considering the objective of accelerating the uptake of CCS. The short-listed CO_2 reuse technologies are at varying stages of development and maturity as shown in the diagram below.



Note: The light blue circle represents the technology at demonstration scale, while the dark blue circle represents commercial operation of the technology based on claims from the respective proponents. Consequently, the predictions appear optimistic. The arrow extending from the dark blue circle indicates a more pragmatic timeframe to commercialisation.

- The short-listed CO_2 reuse technologies fall into the following three broad categories:
  1. EOR and urea yield boosting are proven CO_2 reuse technologies already in commercial use and therefore considered to be mature.
  2. Bauxite residue (red mud) carbonation is already in initial commercial operation while renewable methanol is in the process of being constructed at a commercial scale. Both of these technologies are very site specific, and exist due to suitable local conditions.
  3. The remaining short-listed technologies in relative order of advancement (mineral carbonation, concrete curing, ECBM, EGS, polymers, algae and formic acid), are promising technologies that need to be proven further through technical pilots and/or demonstration plants.
- The short-listed CO_2 reuse technologies vary significantly in potential future demand and revenue estimates. The estimated cumulative global demand and gross revenue between now and 2020 for the short-listed technologies are listed below.

CUMULATIVE DEMAND TO 2020	GROSS REVENUE TO 2020*	TECHNOLOGY/APPLICATION
>500Mt	>US$7500M	EOR
20Mt to 100Mt	Up to US$1500M	Urea yield boosting, mineral carbonation and ECBM
5Mt to 20Mt	Up to US$300M	Polymers, renewable methanol, CO_2 concrete curing, bauxite residue carbonation and algae cultivation
<5Mt	Less than US$75M	Formic Acid and EGS

* Revenues based on assumed bulk CO_2 price of US$15/tonne.

Mature reuse technologies, especially EOR, can provide a revenue supplement to the economic viability of early CCS demonstration projects which are necessary to pave the way for later-stage widespread CCS deployment. The early demonstration projects are required to optimise costs through 'learning by doing' as well as to gain community confidence in CCS and to establish enabling legislative and regulatory regimes. While EOR has a role to play in accelerating the near-term development of initial demonstration projects in favourable locations, it is less evident that reuse can provide sufficient demand for CO_2 to materially facilitate later-stage widespread CCS deployment.

CO_2 REUSE AS AN ECONOMIC DRIVER FOR CCS

In order to accelerate CCS in the later widespread deployment stage, the reuse technologies must not only demand large quantities of CO_2 and generate a revenue stream, but should also be close to commercial operation in order to be aligned with the CCS development timeframe. Furthermore, the magnitude of impact a given technology can have in accelerating the widespread uptake of CCS is also largely a question of economics of the bulk CO_2 market, end product value and drivers such as the implementation of a carbon price.

An evaluation of the economics and commercial framework associated with the reuse of CO_2 formed an integral part of this report (part 2) and highlighted the following key findings:

1. In the near term, revenue from CO_2 reuse will not be a primary driver for CCS deployment. However, where demonstration projects do proceed, reuse revenues can act as a moderate offset to CCS costs, and hence will benefit early demonstration projects rather than projects in the longer term phase of wide-spread commercial deployment. That is because the potential long-term

revenue generated by emitters in supplying CO_2 to reuse technologies is likely to experience downward pressure due to the large long-term CO_2 supply surplus. Introduction of a carbon price will depress the current bulk CO_2 market price due to increased need for emitters to dispose of their CO_2 to avoid paying the carbon penalty.

2. Widespread commercial deployment of CCS will require a global carbon price much larger than the prospective bulk market price of CO_2 for reuse. Revenue generated from CO_2 reuse, mainly from EOR, is likely to provide moderate economic support to early demonstration projects, but in the longer term the introduction of a carbon price will be the critical driver for the widespread uptake of CCS across the full range of stationary CO_2 sources. The current estimated cost gap for CCS from power, steel and cement plants is several times larger than the current bulk CO_2 market price, and downward pressure on this market price is likely to eventuate as and when carbon prices increase. For industrial sources where capture costs are low, a modest initial carbon price may be enough to trigger the further near-term deployment of CCS beyond the current population of gas-related CCS projects.
3. Uncertainty in regulatory acceptance of CO_2 reuse abatement credentials presents challenges for the uptake of reuse technologies. Investments in CO_2 reuse technologies that do not provide permanent storage of CO_2 are ultimately exposed to greater risks due to the uncertainty of the carbon penalty liability between the emitter and the end product. At one end of the spectrum the CO_2 emitter (power station or industrial source) may bear the full carbon price/tax despite passing on the CO_2 for reuse. This will make capture for the purpose of reuse commercially unattractive. At the other end of the spectrum if the carbon price is passed on to the end product then there is exposure to risk that the product may not be as commercially competitive.

CO_2 REUSE AS A DRIVER OF LEARNING AND ACCEPTANCE

Mature forms of CO_2 reuse have the potential to materially advance the development of the earlier phase of initial large-scale demonstration projects, particularly in the absence of strong carbon pricing. These demonstration projects play a critical role in the development of practical regulatory regimes, in gaining community acceptance of CCS and in project and cost optimisation through 'learning by doing'.

The key findings of this report's analysis of the impact of CO_2 reuse technologies on initial CCS demonstration development are as follow:

1. CO_2 reuse for EOR combined with measuring, monitoring and verification (MMV) can provide learnings associated with storage and can help foster community acceptance of storage. The use of CO_2 in EOR, when combined with MMV to track migration of the CO_2 plume, illuminates the geological detail of the storage reservoir and enhances understanding of the factors influencing sub-surface CO_2 migration. The Weyburn-Midale and Cranfield projects are existing examples of this potential.
2. CO_2 reuse through EOR, and to a lesser extent other reuse technologies, may also provide opportunities for capture development and learning. While low-cost sources of concentrated CO_2 (such as natural gas processing, fertiliser plants) will generally provide the most competitive supply for reuse, there will also be circumstances where revenue from reuse and public funding are combined to develop demonstration projects based on capturing CO_2 from power, steel and cement plants. Such demonstration projects will provide additional or earlier opportunities for capture learning, and non-EOR reuse applications may also enable capture projects to proceed in locations where viable geological storage is not immediately accessible.

3. CO_2 reuse is likely to be a key component of CCS demonstration projects in emerging and developing economies where there is strong demand for energy and construction materials and less likelihood of the early adoption of carbon pricing. EOR will be the key interest, but carbonate mineralisation, CO_2 concrete curing, bauxite residue carbonation, ECBM, urea yield boosting and renewable methanol may be of particular interest to emerging economies. However, some of these technologies are still in the early stages of development and may not be at the required maturity for deployment at commercial scale to coincide with CCS development timeframes.

RECOMMENDATIONS

Recommendations for priority action are:

1. Map regional opportunities for CO_2 reuse projects, identifying the point sources of CO_2, especially concentrated sources, align with strong demand for products derived from CO_2. By necessity, the evaluation of technologies and commercial aspects in this report was undertaken at a global level. Local project opportunities may present themselves when targeting specific regions, where strong demand for CO_2-derived products aligns with point sources of CO_2. The identification of low-cost, high concentration CO_2 sources, such as those associated with gas processing, coal gasification and fertiliser production, will be particularly important in identifying viable opportunities, particularly in emerging economies.
2. Encourage the deployment of CO_2-EOR outside of North America and maximise its associated learning and community acceptance opportunities. The present study has identified CO_2-EOR as the CO_2 reuse technology best placed to accelerate conventional CCS due to its maturity and large capacity for CO_2 utilisation and is likely to be important in facilitating early demonstration projects. The CO_2-EOR industry in North America is mature; however, deployment outside of North America has been limited to date. The adoption of rigorous measuring, monitoring and verification (MMV) of the subsurface CO_2 plumes generated by EOR is the key to maximising the storage learning and community acceptance benefits they can provide.
3. Make CO_2 reuse opportunities more of a focus in programs that facilitate the development of large-scale CCS demonstration projects in emerging and developing economies. The mapping and ranking of point source CO_2 emissions and reuse opportunity alignments should provide a valuable tool in prioritising support and/or funding to facilitate the development of large-scale CCS demonstration projects in developing and emerging economies.

1. INTRODUCTION

1.1 BACKGROUND

In July 2009, the 17 partners of the Major Economies Forum (MEF) on Energy and Climate agreed that transition to a low-carbon economy "provides an opportunity to promote continued economic growth as part of a vigorous response to the dangers created by climate change."

A number of action plans were developed with the intention of stimulating efforts to advance a broad range of clean energy technologies, including carbon capture and storage (CCS). The Carbon Capture, Use and Storage Technology Action Plan (CCUS) sought to analyse the emissions reduction potential of CCS, discuss barriers to development and deployment of CCS technologies, and describe best practices and policies that are successfully advancing CCS globally. As a result, priority actions for acceleration of CCS were recommended both domestically and internationally.

One priority action outlined in this Action Plan was to:

'…encourage the use of captured CO_2 to generate revenue that can partially offset the cost of CO_2 capture, as a transitional measure to assist the accelerated uptake of CCS.'

As an early response to the CCUS Technology Action Plan the Global CCS Institute, on behalf of the Government of Australia, the United States, and the United Kingdom, has undertaken an independent assessment of the potential for the use of captured CO_2 (CO_2 reuse) to accelerate the uptake of CCS.

1.2 PURPOSE

As noted above in Section 1.1, one recommendation of the CCUS Technology Action Plan was to:

"...encourage the use of captured CO_2 to generate revenue that can partially offset the cost of CO_2 capture, as a transitional measure to assist the accelerated uptake of CCS."

The purpose of this report is to investigate existing and emerging uses for CO_2 and to address the question of how, and to what extent, CO_2 reuse technologies can accelerate the uptake of CCS.

The Intergovernmental Panel on Climate Change (IPCC) Special Report on CCS (2005) included a chapter dedicated to mineralisation and industrial uses of CO_2. The context of the IPCC report was consideration of industrial use as a CO_2 mitigation technique, and the findings in this context were not encouraging.

It is important to note that this report is not about the CO_2 mitigation potential of industrial use of CO_2. Although mitigation potential is a factor in the overall picture, the primary question this report seeks to answer is how the industrial use of CO_2 might accelerate the uptake of CCS. It may seem counter-intuitive that using CO_2 instead of sequestering it (i.e. taking the 'S' out of 'CCS') could accelerate CCS. This issue will be explored in detail, but to address this concern up front, below are three examples of how the use of CO_2 might directly or indirectly accelerate the deployment/uptake of CCS:

1. EOR can provide a revenue supplement for CCS projects in favourable locations and, when combined with MMV, can provide valuable storage learning as well as underpinning wider community acceptance of geological storage.

2. Deployment of a greater number of CO_2 capture plants may lead to accelerated learnings and a faster rate of cost reduction for capture technology.
3. Some reuse technologies may also result in permanent carbon sequestration, such that they may be regarded as an alternative form of CCS.

1.3 SCOPE AND CONTEXT

Part 1 of this report investigates existing and emerging CO_2 reuse technologies including determining the current status of the technologies globally. Part 1 also considers the current and future potential market size for each reuse technology in order to understand the CO_2 utilisation potential. Technologies are short-listed based on their potential to demand CO_2 on a scale commensurate with the emissions generated from power plants and other large industrial CO_2 sources, a key to their ability to contribute in some form to accelerating CCS.

The short-listed technologies undergo a categorisation, a high-level comparison and a more detailed evaluation and analysis process. The technology categorisation outlines key differences between the short-listed technologies which will have an impact on the technologies' ability to accelerate the uptake of CCS. The technology comparison is a high level comparison focusing on technology maturity, potential for revenue generation, level of investment required to achieve commercialisation, CO_2 emissions from reuse technologies and applicability of the technologies to developing countries. The technology evaluation builds on the technology comparison and considers a broad range of factors, including scale and potential demand, commercial viability, environmental and social issues such as CO_2 equivalent emissions resulting from the reuse technology. An initial assessment of the technologies' potential to (1) accelerate cost reductions for CCS and (2) accelerate alternative forms of CCS is also undertaken.

Part 2 of the report builds on the assessments in Part 1 and considers the broader economic and commercial framework for CO_2 reuse. An understanding of the key costs and revenues associated with CCS is provided to explore the potential impact that different CO_2 reuse technologies can have in accelerating the uptake of CCS. Part 3 of the report assimilates key findings from throughout the report to arrive at recommendations for further action.

The descriptions and evaluation of the technologies presented herein represent only a snapshot in time, and their progress in the forthcoming years may lead to different conclusions if the technologies are reconsidered in the future. Furthermore, the level of evaluation has been limited by the level of information available about technologies, which is inevitably tied to their overall development status (the publicly available information about technologies closer to commercialisation tend to be more abundant). For example, some promising CO_2 to liquid-fuels technologies were identified, including catalysed solar reforming and engineered photosynthetic microorganisms for direct fuel secretion, however the level of information available about the technologies made further evaluation impractical.

When considering the economic and commercial framework for CO_2 reuse, generally a global perspective has been taken, with some consideration of likely typical regional conditions. However, it is not feasible to consider for example the supply/demand balance of each sub-region of each sovereign state around the globe. Because of the global perspective taken in such analyses, it should be noted that local conditions superior for the deployment of CO_2 reuse may occur, where the demand for products derived from CO_2 may be high.

The economic and commercial perspectives for early CCS demonstration project development are distinctive in that they are centred largely on EOR due to its maturity, and where, in the absence of carbon constraints, CO_2 for reuse provides a modest revenue stream. While this report highlights the value of the relatively well-defined potential of EOR to accelerate early CCS demonstration project development, the bulk of the report covers the longer-term opportunities that could ultimately arise from the full suite of emerging CO_2 reuse technologies.

1.3.1 INCLUSIONS

This report considers technologies that use anthropogenic CO_2, where the CO_2 is concentrated to some degree (greater than its atmospheric concentration). In particular, the report considers technologies that utilise CO_2 otherwise emitted from large point sources, such as power stations, refineries, gas processing plants and fertiliser plants. It differentiates between high concentration sources, such as gas processing plants and fertiliser plants, which can be supplied at relatively low cost (<US$20/tonne) and the low concentration sources such as power, steel and cement plants that require capture technologies to concentrate the CO_2 and for which the supply cost is relatively high (US$50–100/tonne).

The report considers non-captive uses for CO_2, e.g. uses where the CO_2 needs to be sourced external to the process. The distinction between 'non-captive' and 'captive' CO_2 (as defined in Section 1.4) is important to note, as statistics for urea manufacture show a global requirement for over 100 Mtpa of CO_2. On the face value this appears to be an excellent market for captured CO_2. However, this CO_2 is produced from the fossil fuel feedstock to the urea production process, and therefore CO_2 does not need to be sourced externally. In reality, the CO_2 balance of urea production is not so straightforward, and some potential for CO_2 use remains. Urea production is one of the short-listed technologies considered within this report and refers to the opportunity to utilise non-captive sources of CO_2 only. This is discussed further in section 2.2 in the report.

1.3.2 EXCLUSIONS

The report does not consider the use of atmospheric CO_2, as this classification is so broad that it covers essentially all photosynthetic activity, and fails to address the specific aim of accelerating CCS technology as applicable to large point sources.

The report does not consider captive uses for CO_2, e.g. uses where the CO_2 is an intermediate product in the process (as explained above in section 1.3.1). This is because captive processes do not offer any opportunity to provide additional demand for captured CO_2 into the future.

1.4 DEFINITIONS USED IN THIS REPORT

1.4.1 CO_2 REUSE

The definition of CO_2 reuse used for this report is as follows:

Any practical application of captured, concentrated CO_2 that adds value (such as revenue generation, or environmental benefit), and which can partially offset the cost of CO_2 capture, as a transitional measure to assist the accelerated uptake of CCS.

This definition is best described as a statement of what would constitute an 'ideal' CO_2 reuse technology.

For the purposes of undertaking a stock-take of CO_2 reuse applications, a broader definition of CO_2 reuse was adopted as follows:

Any practical application of captured, concentrated CO_2 that adds financial benefits (e.g. revenue generation) or provides environmental, social or other benefits.

1.4.2 CCS

The definition of CCS as considered in this report is the capture, compression, transportation, and long term storage of CO_2 in suitable subterranean geological reservoirs.

1.4.3 ALTERNATIVE FORMS OF CCS

Reuse technologies that also permanently store CO_2 are considered to be an alternative form of CCS, referred to as 'alternative CCS.' Permanent storage is most simply defined as storage considered permanent under an emissions trading scheme or greenhouse emission legislation. This is likely to require that a product retain its carbon dioxide equivalent content for at least hundreds of years, or have an extremely slow CO_2 release rate.

1.4.4 CAPTIVE AND NON-CAPTIVE

Captive use refers to processes wherein CO_2 is only an intermediate product in a chemical manufacturing process, and where it is ultimately consumed in a later process step (e.g. urea processing). As CO_2 is not a feedstock but an intermediate product, captive processes offer no opportunity for providing additional demand for CO_2 in the future.

Non-captive CO_2 use is where the CO_2 needs to be sourced external to the process.

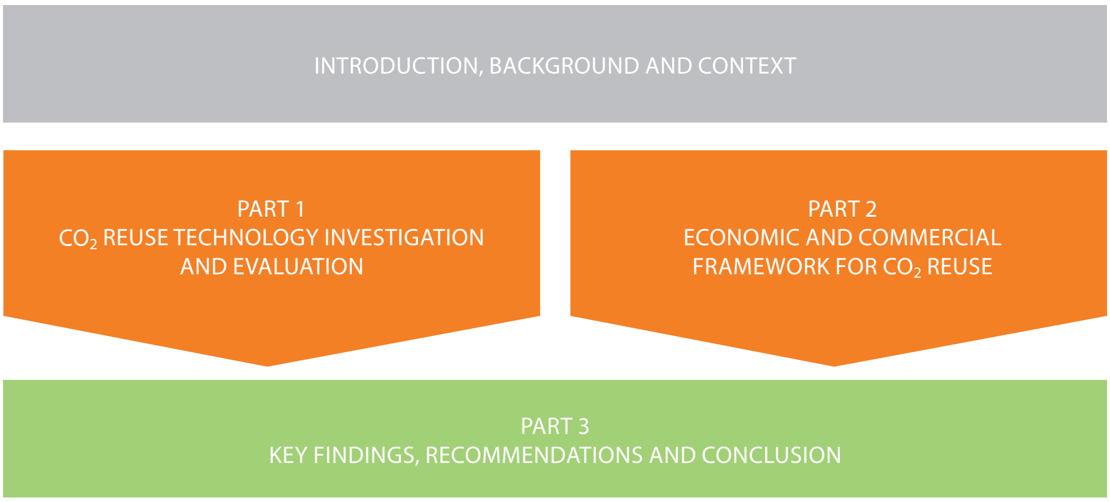
1.4.5 BULK CO_2

Bulk CO_2 is considered to be unprocessed gaseous CO_2, with a CO_2 content typically in excess of 95 per cent.

1.5 STRUCTURE OF THIS REPORT

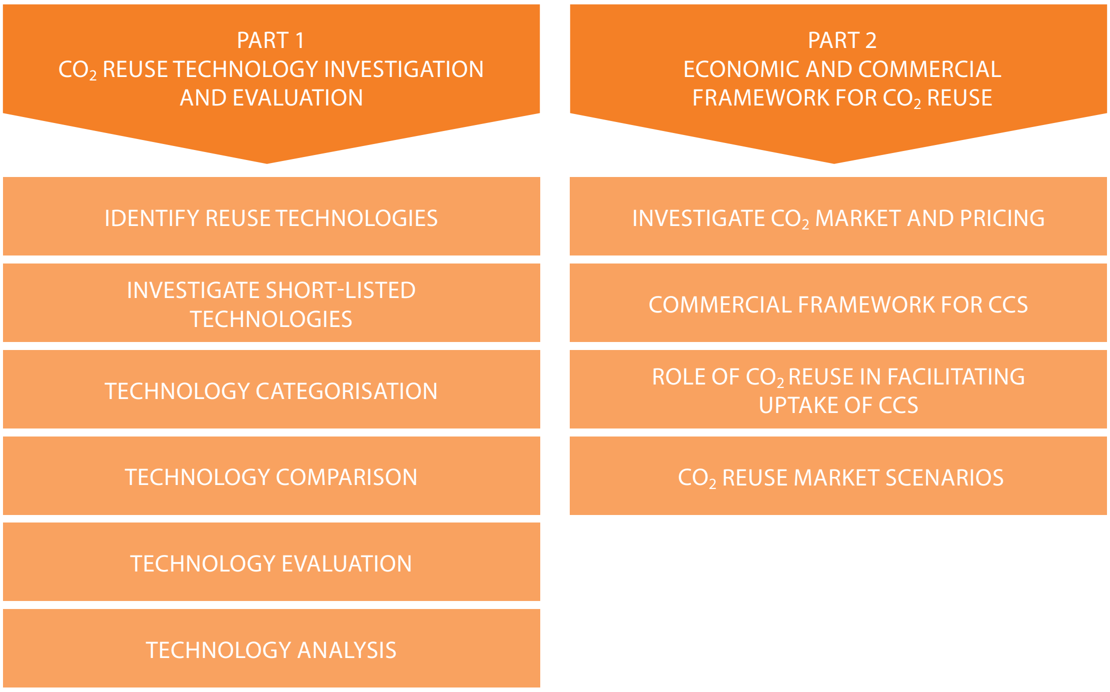
This report is presented according to the process outlined in Figure 1.1

Figure 1.1 Report structure



Part 1 and part 2 of the report are presented as follows:

Figure 1.2 Part 1 and 2 structure



PART 1
TECHNOLOGY INVESTIGATION AND EVALUATION

1. CO_2 REUSE TECHNOLOGIES

Near-term CO_2 demand for use in EOR will help to support the development of initial CCS demonstration projects in favourable locations. However, for any CO_2 reuse technology to have the potential to materially accelerate CCS deployment in the longer term, it must have the potential to demand large quantities of CO_2, e.g. on a scale commensurate with capture from power generation and other large industrial sources.

The following shortlist of ten CO_2 reuse technologies could potentially meet this requirement: enhanced oil recovery (EOR), urea yield boosting, enhanced geothermal systems, polymer processing, algae cultivation, carbonate mineralisation, CO_2 concrete curing, bauxite residue carbonation, CO_2 as a feedstock for liquid fuel production, and enhanced coal bed methane.

There are already many industrial uses for CO_2, with the current global 'non-captive' consumption estimated to be approximately 80Mtpa; comprising 25Mtpa in the liquid and solid form and the remainder in gaseous and supercritical form.[1]

This section endeavours to account for all of the existing and emerging CO_2 reuse technologies and applications that utilise CO_2 as a feedstock or directly to manufacture an end product, at the time of compiling this report. It is recognised that new and potentially 'breakthrough' technologies may be developed in the future.

This section also considers the current and future potential market size of both the existing and emerging CO_2 reuse technologies in order to understand the long-term CO_2 utilisation potential and to determine if quantities are likely to be commensurate with the emissions generated from power plants or other large industrial sources. The scale of CO_2 utilisation will significantly affect the impact that these technologies may have in potentially accelerating the long-term uptake of CCS.

1.1 LIST AND DESCRIPTION OF TECHNOLOGIES

Table 1.1 and Table 1.2 represent a list of existing and emerging potential uses for CO_2 respectively. These lists are current as at the time of compiling the report. Each may not be entirely exhaustive of all possible applications for CO_2, but identifies established common uses, and in the case of future potential technologies, identifies those most publicised and that upon preliminary examination appear to be more than just a 'pie in the sky' idea. As time progresses new technologies are likely to materialise and the emerging technologies identified are likely to be developed and advanced further than acknowledged within.

1 Note this does not include the large 'captive' volumes of CO_2 generated and subsequently consumed in the same industrial process, most notable urea production, which globally produces and then consumes an estimated 113Mtpa of CO_2.

Table 1.1 Existing uses for CO_2

EXISTING USES	BRIEF DESCRIPTION
Enhanced oil recovery (EOR)	CO_2 is injected into depleted oil fields. The CO_2 acts as a solvent that reduces the viscosity of the oil, enabling it to flow to the production well. Once production is complete, the CO_2 can potentially be permanently stored in the reservoir.
Urea yield boosting (non-captive use only)[2]	When natural gas is used as the feedstock for urea production, surplus ammonia is usually produced. A typical surplus of ammonia may be 5 per cent to 10 per cent of total ammonia production. If additional CO_2 can be obtained, this can be compressed and combined with the surplus ammonia to produce additional urea. A number of projects have been implemented to capture CO_2 from ammonia reformer flue gas for injection into the urea production process.
Other oil and gas industry applications	CO_2 is used as a fluid for the stimulation/fracturing of oil and gas wells. It is typically trucked to site and injected as liquid carrying propping agents (sand and other materials which prop open the pores of the rock to prevent closure after stimulation).
Beverage carbonation	Carbonation of beverages with high-purity CO_2.
Wine making	CO_2 is used as a seal gas to prevent oxidation of the wine during maturation. CO_2 is also produced during the fermentation process, and it is already captured on-site for reuse for its inert gas properties.
Food processing, preservation and packaging	CO_2 is used for various applications in the food industry, including cooling while grinding powders such as spices and as an inert atmosphere to prevent food spoilage. In packaging applications, CO_2 is used in modified atmosphere packaging (MAP) with products such as cheese, poultry, snacks, produce and red meat, or in controlled atmosphere packaging (CAP), where food products are packaged in an atmosphere designed to extend shelf life. Carbon dioxide is commonly used in MAP and CAP because of its ability to inhibit growth of bacteria that cause spoilage.
Coffee decaffeination	Supercritical CO_2 is used as the solvent for decaffeinating coffee. It is preferred due to its inert and non-toxic properties.
Pharmaceutical processes	Use of CO_2 in the pharmaceutical industry may overlap with other uses identified, as it typically includes inerting, chemical synthesis, supercritical fluid extraction, product transportation at low temperature, and acidification of wastewater. 80–90 per cent of material consumption by mass in the pharmaceutical industry is attributable to solvent consumption. US pharmaceutical solvent consumption in 1995 was ~80,000tpa, but supercritical CO_2 was not used in significant enough quantities to be reported.

2 Unless otherwise stated, all references made to urea production within the report refer to the incremental additional production of urea from surplus ammonia and non-captive CO_2, e.g. the supply of CO_2 from a source external to the process, not generated and subsequently used within the process itself.

EXISTING USES	BRIEF DESCRIPTION
Horticulture	CO_2 is provided to greenhouses to maintain optimal CO_2 concentration and maximise plant growth rate. Sources include on-site cogeneration schemes as well as off-site industrial sources connected via pipeline networks.
Pulp and paper processing	CO_2 is used to reduce pH during pulp washing operations.
Water treatment	CO_2 is used for re-mineralisation of water following reverse osmosis and for pH control (reduction).
Inerting	CO_2 is used in a wide range of applications where the physical properties of an inert gas are desirable. This includes applications covered under other use categories, such as a welding shielding gas and gas used in food packaging and in wine production.
Steel manufacture	CO_2 is used in a minority of basic oxygen furnaces as a bottom stirring agent. It is also used for dust suppression.
Metal working	Used for varied purposes, including chilling parts for shrink fitting, and hardening of sand cores and moulds.
Supercritical CO_2 as a solvent	CO_2 is useful for high-pressure extraction and as a solvent to isolate targeted compounds, such as fragrances and flavours. Because of its low critical temperature and moderate pressure requirements, natural substances can be treated particularly gently. It is gaining favour as a solvent in the dry cleaning industry for this reason.
Electronics	Printed circuit board manufacture uses small quantities of CO_2 in niche applications, predominantly as a cleaning fluid.
Pneumatics	Pneumatic applications for CO_2 include use as a portable power source for pneumatic hand tools and equipment, as well as a power source for paintball guns and other recreational equipment.
Welding	Used as a shrouding gas to prevent oxidation of the weld metal.
Refrigerant gas	CO_2 is used as the working fluid in refrigeration plant, particularly for larger industrial air conditioning and refrigeration systems. It replaces more toxic refrigerant gases that also have much greater global warming potential.
Fire suppression technology	When applied to a fire, CO_2 provides a heavy blanket of gas that reduces the oxygen level to a point where combustion cannot occur. CO_2 is used in fire extinguishers, as well as in industrial fire protection systems.

Table 1.2 Emerging uses for CO_2

EMERGING USES	BRIEF DESCRIPTION
Enhanced coal bed methane recovery (ECBM)	In CO_2-ECBM, CO_2 is injected into coal seams, where it preferentially adsorbs onto the coal, displacing and releasing adsorbed methane, which can then be recovered at the surface. A key constraint on practical application of this concept has been the decrease in permeability and injectivity that accompanies CO_2 induced swelling of the coal. Nitrogen (N_2) can also be used for ECBM, but it utilises a different mechanism, by reducing the partial pressure of the gaseous methane. This has led to the consideration of direct flue-gas injection for CO_2, which would utilise both the mechanisms of CO_2 and N_2-ECBM.
Enhanced geothermal systems (EGS) – CO_2 as a working fluid	There are two ways in which supercritical CO_2 may be utilised in EGS geothermal power generation. Firstly, it may be used as the circulating heat exchange fluid. The benefit here is that the significant density difference between the cold CO_2 flowing down the injection well(s) and the hot CO_2 flowing up the production well(s) would eliminate the need for a circulation pump. Secondly, this concept could be extended, and the circulating CO_2 could also be used directly as the working fluid in a supercritical CO_2 power cycle. There is significant interest in supercritical CO_2 power cycles because of the potential for high efficiency and compact turbo machinery.
Power generation – CO_2 as a working fluid	Supercritical CO_2 power cycles need not be limited to geothermal power plants, as the benefits of high efficiency and compact turbo machinery are not heat source-specific. The nuclear power industry is particularly interested in supercritical CO_2 power cycles for this reason.
Polymer processing	One example of CO_2 as a feedstock for polymer processing involves the transformation of carbon dioxide into polycarbonates using proprietary zinc based catalyst system. A variety of other process routes and end products have been proposed.
Chemical synthesis (excludes polymers and liquid fuels/hydrocarbons)	Carbon and oxygen are both key elements in organic chemistry. Consequently, there are a wide range of chemicals that can at least theoretically utilise CO_2 as a feedstock for production, including organic acids, alcohols, esters, and sugars. The practicality of CO_2 as a feedstock will vary significantly based on the current production routes. The dominant potential demand, based on current markets, could come from acetic acid, which has a current global market of ~6Mtpa. Acetic acid can be produced by direct catalysis of CO_2 and methane.
Algal bio-fixation	The productivity of algal cultivation systems can be increased significantly (up to a saturation point) by the injection/addition of CO_2 to the growth medium/solution.

EMERGING USES	BRIEF DESCRIPTION
Mineralisation	
Calcium carbonate and magnesium carbonate	Mildly concentrated CO_2 (e.g. power station flue gas) is contacted with mineral-loaded alkaline brine. The CO_2 present in the gas precipitates out as mineral carbonates (limestone / dolomite equivalent precipitates). The resulting product can be further processed to form an aggregate equivalent product for the construction industry, and can also potentially displace a small portion of Portland Cement in concrete.
Baking soda (sodium bicarbonate)	This is a variant of mineralisation wherein CO_2 is contacted with sodium rich brine, resulting in the formation of sodium bi-carbonate ($NaHCO_3$).
CO_2 concrete curing	This technology is focused on precast concrete production facilities, where the waste CO_2 from onsite flue gas is permanently stored as un-reactive limestone within the concrete. This also limits the need for heat and steam in the curing process. The result is a reduction in emissions of CO_2 equivalent to up to 120kg of CO_2 per tonne (286 lbs CO_2 per US ton) of precast concrete.
Bauxite residue treatment ('red mud')	The extraction of alumina from bauxite ore results in a highly alkaline bauxite residue slurry known as 'red mud'. Concentrated CO_2 can be injected into the red mud slurry to partially neutralise the product, improving its manageability, reducing its disposal costs and limiting its potential environmental impacts. In the neutralisation process, the CO_2 is converted to mineral form (typically carbonates). The resulting product remains slightly alkaline, and has potential as a soil amendment for acidic soils.
Liquid fuels	
Renewable methanol	Electrolysis of water produces H_2. The H_2 is combined with captured CO_2, compressed and reacted over a catalyst at moderate temperature and pressure (~5MPa, ~225°C) to produce methanol and water.
Formic acid	Electro-reduction of CO_2 to produce formic acid (HCOOH) and O_2. Formic acid is used as a hydrogen carrier, with hydrogen the primary fuel. Formic acid has been classified as a liquid fuel as hydrogen is only released from the liquid formic acid as required.
Genetically engineered micro-organisms for direct fuel secretion	Engineered product-specific photosynthetic organisms circulate in a solution of micronutrients and brackish water, producing hydrocarbon products as a by-product of metabolism. Energy input is direct, un-concentrated solar energy.
CO_2 injection to conventional methanol synthesis	The yield of methanol from conventional methanol synthesis can be increased (some estimates suggest up to a 20 per cent yield increase) by the injection of additional CO_2 upstream of the methanol reformer. Industry consensus is that new plants will generally have an autothermal reformer, which tends to produce an excess of hydrogen such that CO_2 injection will not be required.

Table 1.3 and Table 1.4 provide an estimate of the current and maximum potential CO_2 demand from each of the existing and emerging CO_2 reuse technologies.

It should be noted that reliable and detailed end-use statistics on CO_2 production and consumption are not readily available for many of the specific application, so the figures provided in Table 1.3 and Table 1.4 are indicative and provide an indication of the order of magnitude of the current CO_2 consumption and potential future CO_2 utilisation.

Consequently, these estimates are only considered 'order of magnitude' estimates. The specific values have not been presented herein, rather the range within which the demand of any given application is thought to fall is selected from the following standard set of demand ranges:

- Demand < 1Mtpa
- 1Mtpa < demand < 5Mtpa
- 5Mtpa < demand < 30Mtpa
- 30Mtpa < demand < 300Mtpa
- demand >300Mtpa

Table 1.3 Current and future potential CO_2 demand of existing uses

EXISTING USES	CURRENT NON-CAPTIVE CO_2 DEMAND (MTPA)	FUTURE POTENTIAL NON-CAPTIVE CO_2 DEMAND (MTPA)
Enhanced oil recovery (EOR)	30< demand < 300	30< demand < 300
Urea yield boosting	5 < demand < 30	5 < demand < 30
Other oil and gas industry applications	1< demand <5	1< demand <5
Beverage carbonation*	~8	~14
Wine making	<1	<1
Food processing, preservation and packaging*	~8.5	~15
Coffee decaffeination	unknown	1< demand <5
Pharmaceutical processes	<1	<1
Horticulture	<1	1< demand <5
Pulp and paper processing	<1	<1
Water treatment	1 < demand < 5	1 < demand < 5
Inerting	<1	<1
Steel manufacture	<1	<1
Metal working	<1	<1
Supercritical CO_2 as a solvent	<1	<1
Electronics	<1	<1
Pneumatics	<1	<1
Welding	<1	<1
Refrigerant gas	<1	<1
Fire suppression technology	<1	<1

*Actual estimates provided for beverage carbonation and food processing and packaging, as reasonable information is available for these uses

Table 1.4 Future potential CO_2 demand of emerging uses

EMERGING USES	FUTURE POTENTIAL NON-CAPTIVE CO_2 DEMAND (MTPA)
Enhanced coal bed methane recovery (ECBM)	30 <demand <300
Enhanced geothermal systems – CO_2 as a heat exchange fluid	5< demand <30
Power generation – CO_2 as a power cycle working fluid	<1
Polymer processing	5< demand <30
Chemical synthesis (excludes polymers and liquid fuels/ hydrocarbons)	1< demand <5
Algae cultivation	>300
Mineralisation	
Calcium carbonate and magnesium carbonate	>300
Baking soda (sodium bicarbonate)	<1
CO_2 concrete curing	30< demand <300
Bauxite residue treatment ('red mud')	5 < demand < 30
Liquid Fuels	
Renewable methanol	>300
Formic acid	>300
Genetically engineered micro-organisms for direct fuel secretion	>300
CO_2 injection to conventional methanol synthesis	1< demand <5

The 'order of magnitude' is very pertinent to the discussion on CO_2 reuse, as there is a significant discrepancy in scale between current industrial CO_2 consumption and CO_2 capture quantities from a commercial-scale CCS plant. For example, a single 300MW (net) CCS demonstration project may capture approximately 2.5Mtpa of CO_2. This single 300MW (net) demonstration project represents a rate of CO_2 production that is greater than the current non-captive industrial consumption of Japan, South Korea and Australia combined.

1.2 FIRST CUT OF TECHNOLOGIES FOR DETAILED INVESTIGATION AND EVALUATION

A threshold of 5Mtpa global CO_2 reuse potential was applied to the list of reuse technologies to focus the report on applications with large-market potential. The CO_2 utilisation potential should be of a scale commensurate with future CO_2 capture requirements from power generation and other large industrial sources.

Table 1.1 and Table 1.2 identify numerous options for the use of CO_2. However, it is evident in Table 1.3 and Table 1.4 that many of the reuse applications and technologies have a limited demand and in the context of CO_2 volumes associated with CCS plants, the demand is immaterial. While localised CO_2 demand for EOR can make an important contribution to the development of early CCS demonstration projects, for a reuse technology to have any other material impact on accelerating the long-term uptake of CCS, the CO_2 utilisation potential of the technology should be of a scale commensurate with CO_2 capture from power generation and other large industrial sources.

To permit a more comprehensive study on those technologies which have the most potential, a threshold of 5Mtpa global CO_2 reuse potential was applied. On this basis, the technologies short-listed for further analysis and evaluation are as follows:

- CO_2 enhanced oil recovery;
- CO_2 as a feedstock for urea yield boosting;
- Enhanced geothermal systems (using CO_2 as a working fluid);
- CO_2 as a feedstock in polymer processing;
- Algae production;
- Mineralisation (including carbonate mineralisation / concrete curing / bauxite residue carbonation);
- Liquid fuels (including renewable methanol / formic acid); and
- CO_2 enhanced coal bed methane (ECBM) recovery.

Any CO_2 reuse application with a market potential below the 5Mtpa threshold will not be investigated further as its size is immaterial in the context of CCS.

One exception that should be noted in relation to the above shortlist is that beverage carbonation and food processing and packaging as both have current global consumption levels of CO_2 in excess of 5Mtpa. However, they are mature industries with an established supply chain, and with more modest growth rates expected into the future, the incremental demand for each will not necessarily ever exceed 5Mtpa, certainly not in the near term. For this reason, these reuse applications were excluded from the shortlist.

Another technology not explicitly listed above is CO_2 enhanced gas recovery (EGR), which is distinct from ECBM. Please refer to Section 2.1 for a brief discussion on EGR, and how it has been treated for the purposes of this study.

2. DESCRIPTION OF SHORT-LISTED TECHNOLOGIES

The following section provides an overview of each of the short-listed CO_2 reuse technologies. The overview includes a general description and the status of the technology, the required CO_2 source and the degree of CO_2 utilisation. It also identifies the proponents currently involved, the end products, any funding support provided and general barriers and benefits of the reuse technology.

Further detailed information of each CO_2 reuse technology can be found in Appendices A to J (as indicated below):

- CO_2 for use in enhanced oil recovery (EOR) – Appendix A.
- CO_2 as feedstock for urea yield boosting – Appendix B.
- CO_2 as a working fluid for enhanced geothermal systems – Appendix C.
- CO_2 as feedstock for polymer processing – Appendix D.
- CO_2 for use in algae cultivation – Appendix E.
- CO_2 as feedstock for carbonate mineralisation – Appendix F.
- CO_2 for use in concrete curing – Appendix G.
- CO_2 for use in bauxite residue carbonation – Appendix H.
- CO_2 as feedstock for liquid fuel production – Appendix I.
- CO_2 for use in enhanced coal bed methane recovery – Appendix J.

A list of demonstration projects and R&D studies for emerging CO_2 reuse technologies are located in Appendix L. This list is based on a desktop study only and is by no means exhaustive.

2.1 CO_2 FOR USE IN ENHANCED OIL RECOVERY

Enhanced oil recovery (EOR) is the method by which depleted oil fields are injected with compressed CO_2, to extract reserves which are otherwise inaccessible. CO_2-EOR was first deployed in the 1970's and is considered a commercially mature technology. Generally EOR relies on the solvent properties of CO_2 to dissolve in and decrease the viscosity of the oil (miscible CO_2 flooding) as shown in Figure 2.1 below. However, immiscible CO_2 flooding may be utilised for heavy crude oil, with the mechanism for oil recovery more associated with gravity displacement.

Figure 2.1 Enhanced oil recovery overview

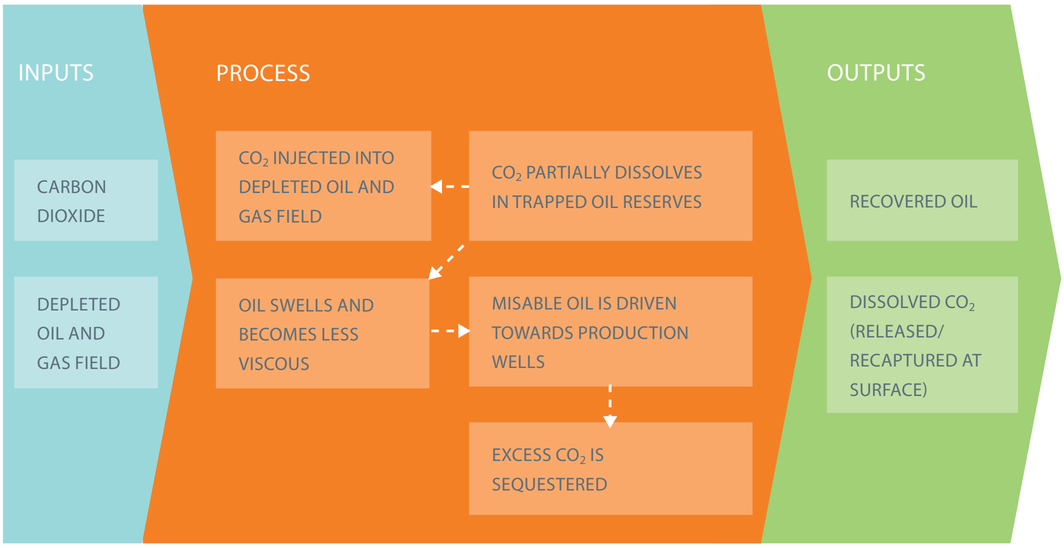


Table 2.1 Enhanced oil recovery summary

CRITERIA	DESCRIPTION
GENERAL DESCRIPTION	
Technology	Enhanced oil recovery
Proponents	Oil companies have pioneered EOR in the USA using CO_2 from naturally occurring CO_2 reservoirs. Additional anthropogenic CO_2 supply for EOR is available from companies employing capture on an industrial plant (e.g. syngas, natural gas sweetening, coal power, fertiliser, or cement production) with access to transport infrastructure within range of suitable oil fields. Existing demonstration size or greater EOR projects, include: Andarko Petroleum Corporation (Salt Creek, USA), Chevron (Rangely-Webber EOR, USA), Chinese Government (Daqing EOR, China), EnCana (Weyburn, Canada), Penn West Energy Trust (Pembina Cardium EOR, USA)
Description	CO_2 is injected into oil reservoirs to enable recovery of additional oil not recovered by primary production or water flooding. The CO_2 acts as solvent, decreasing oil viscosity. CO_2 is separated from the oil at the surface for re-injection. Large volumes of CO_2 can be stored in the reservoir upon completion of the EOR activities.
Products	Crude oil
CO_2 utilisation per tonne of product output	CO_2 injection per oil displacement rate is very dependent on reservoir's characteristics (e.g. size, pressure, temperature, etc). The Weyburn, Canada project injects around 0.5 tCO_2 per incremental barrel oil displaced (Enhanced Oil Recovery Institute, 2007). As stated, this varies dramatically and would need to be examined on a site-by-site basis.
CO_2 source	Commercial scale CO_2-EOR injection, such as that occurring in West Texas, predominantly use naturally occurring CO_2 reservoirs, though CO_2 captured from industrial sources can also be used, as it is at Weyburn.

CRITERIA	DESCRIPTION
Technology status (includes project status)	CO_2-EOR is a proven technology with many projects in operation including: The Rangely project in the US has been using CO_2 for EOR since 1986, sourcing the CO_2 from the LaBarge field in Wyoming. 23–25 Mt have been stored since 1986, nearly all of which is considered to be dissolved as aqueous CO_2 and bicarbonate. At Weyburn, about 2.8 Mt a year of CO_2 is captured from a coal gasification plant, transported to Saskatchewan, and injected it into declining oil fields (IEA 2010). Recent projects supported under the American Recovery and Investment Act allow for capture and storage of 4.5M tonnes of CO_2 annually from a methanol plant in Louisiana and 1M tonnes of CO_2 per year from existing steam-methane reformers in Port Arthur, Texas. In both cases, this CO_2 will be used for enhanced oil recovery in the West Hastings oilfield starting in April 2014.
Funding/support	While the majority of EOR projects progress with industry funding alone, a large proportion of proposed CCS projects in North America rely on EOR revenue as well as public funding. The DOE is sponsoring a range of studies and projects involving the application of EOR to CCS development.
General benefits	Increased oil revenue through CO_2 storage. Return on investment through oil production should assist industrial CCS roll-out in the short term, and EOR is likely to materially assist the development of early CCS demonstration projects. Combined with MMV, EOR also has the potential to enhance understanding of sub-surface CO_2 migration and to foster community acceptance of geological storage.
General barriers	EOR is not technically feasible in all depleted or depleting oilfields, and the capital cost of implementing EOR may be prohibitive in many situations, so its deployment will be restricted to favourable locations. That still leaves substantial scope for the expansion of EOR, however, particularly if it can attract revenue from emission mitigation credits as well as from oil production.

Refer to Appendix A for further details of CO_2 for Enhanced Oil Recovery (EOR).

2.1.1 ENHANCED GAS RECOVERY (EGR)

A technology which is analogous to CO_2-EOR is CO_2 enhanced gas recovery (EGR). EGR refers to incremental gas recovery from depleted conventional gas reservoirs. EGR differs from EOR in that the mechanism for the enhanced gas recovery in theory relies on physical displacement (upwards) of the lighter natural gas by the heavier CO_2, with minimal mixing. This is in contrast to EOR, which typically relies on miscible mixing of oil and CO_2 to decrease oil viscosity.

EGR is distinct from ECBM and has received limited attention compared to CO_2-EOR. This is due to its level of immaturity in comparison to ECBM and due to the limited information available. To date only one pilot experiment has been conducted by Gaz De France in the North Sea at the K–12B field in the offshore Netherlands, which has been terminated.

Currently, EGR does not present itself as a lucrative opportunity due to the relatively high initial recovery characteristic of gas reservoirs (typically more than two thirds of the gas in place). The economics of EGR are not strong, or the technology would be further developed. Specific case study simulations for EGR have suggested a breakeven CO_2 price of US$8/t with a wellhead natural gas price of US$2.85/GJ, clearly indicating that revenue from reuse would be very modest.

For the purpose of the current study, EGR is considered to be part of EOR as a short-listed item. Since EGR is so immature in comparison to ECBM and due to limited information available, the technology analysis throughout the report will focus on CO_2 for EOR. However, the potential for EGR may improve in the future as world natural gas prices rise, and it should not be dismissed from future consideration. Furthermore, by their nature, former gas reservoirs have demonstrated a capacity to retain gas, which makes them an obvious target as a CO_2 sequestration site (and the potential complimentary revenue from incremental natural gas recovery will not go unnoticed).

In summary, EGR is undeveloped, has very marginal economics at current gas prices and consequently has not been considered as a separate short-listed technology. However, EGR can effectively be considered as part of EOR as a short-listed item. In particular, if natural gas prices rise into the future, the economics and characteristics of EGR may look very similar to EOR.

2.2 CO_2 AS FEEDSTOCK FOR UREA YIELD BOOSTING

Urea accounts for almost 50 per cent of the world’s nitrogen fertiliser production. It is produced by combination of ammonia and carbon dioxide at high pressure and temperature. Normally, CO_2 is sourced from the process of reforming natural gas (or a similar feedstock) to produce ammonia. In this regard, urea production can predominantly be considered a ‘captive’ use of CO_2 (i.e. CO_2 is produced and then used within the same industrial process).

However, when natural gas is the feedstock for urea production, there is typically a small surplus of ammonia (approximately 5 to 10 per cent), which could be reacted with externally supplied (non-captive) CO_2 to produce additional urea. Reformer flue gas capture plants have been installed at several urea production facilities to capture CO_2 for this purpose, particularly by Mitsubishi Heavy Industries, and the technology can be considered mature.

Figure 2.2 Urea fertiliser production overview

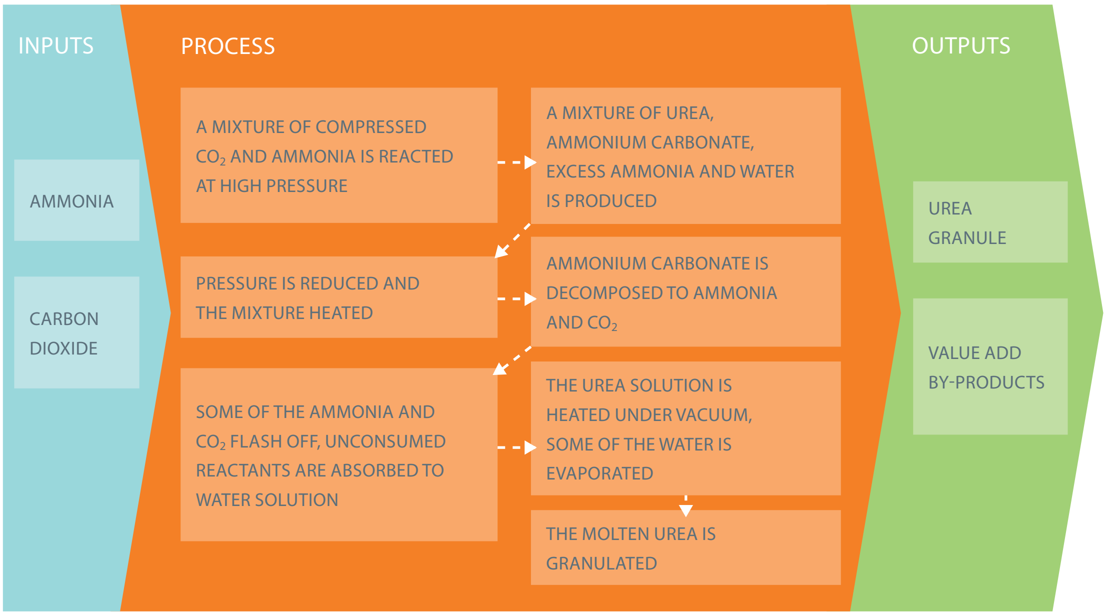


Table 2.2 Urea yield boosting summary

CRITERIA	DESCRIPTION
GENERAL DESCRIPTION	
Technology	Boosting yields of conventional fertiliser production facilities
Proponents	Multi-national industrial scale fertiliser production firms
Description	Urea production plants using natural gas as a feedstock tend to produce a small surplus of ammonia. Captured CO_2 can be reacted with surplus ammonia to form urea. Urea is one of the most common types of solid nitrogen fertilisers. The final product is typically a granulated solid. Once applied to agricultural land, urea reacts with water to release the CO_2 and ammonia. The CO_2 returns to atmosphere and the ammonia decomposes further supplying nitrogen to the crops. Urea can also be used to produce Urea-Ammonium Nitrate (UAN), one of the most common forms of liquid fertiliser.
Products	Urea
CO_2 utilisation per tonne of product output	For every tonne of urea produced, 0.735–0.75 tonnes of CO_2 will typically be consumed.
CO_2 source	The CO_2 source for urea yield boosting is typically CO_2 captured on-site from reformer flue gas.
Technology status (includes project status)	Urea has been produced on an industrial scale for over 40 years. CO_2 capture plants for urea yield boosting have been installed since late 1990's. The technology is relatively mature.

CRITERIA	DESCRIPTION
Funding/support	None
General benefits	None identified
General barriers	None identified

Refer to Appendix B for further details of CO_2 for urea yield boosting.

2.3 CO_2 AS A WORKING FLUID FOR ENHANCED GEOTHERMAL SYSTEMS (EGS)

Enhanced geothermal systems (EGS), also known as hot fractured rocks (HFR) or hot dry rocks (HDR), is an emerging geothermal technology whereby subsurface hot rocks that are not naturally suitable for geothermal energy extraction can be made so through engineering procedures. The requirement for significant engineering work prior to heat extraction distinguishes EGS from conventional geothermal applications. A new approach to this concept is currently being pursued whereby supercritical CO_2 is circulated as the heat exchange fluid (or working fluid) instead of water or brine to recover the geothermal heat from the reservoir. It can also be used as the working fluid of the power cycle in a supercritical CO_2 turbine.

Figure 2.3 Enhanced geothermal systems overview

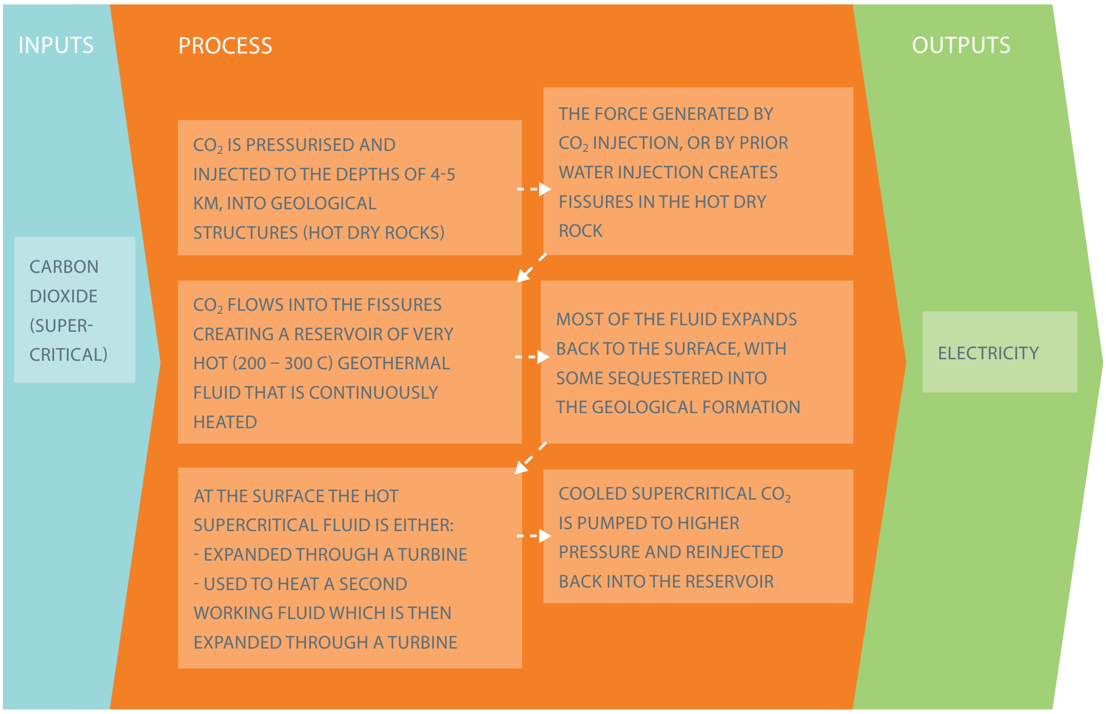


Table 2.3 Enhanced geothermal systems summary

CRITERIA	DESCRIPTION
Technology	Supercritical CO_2 as working fluid in enhanced geothermal systems (EGS)
Proponents	GreenFire Energy / Enhanced Energy Resources (Joint Venture) Geodynamics Limited Symmyx Technologies
Description	Supercritical CO_2 is circulated as the heat exchange fluid (or working fluid) instead of water or brine to recover the geothermal heat from the reservoir. The CO_2 may also be used directly as the power cycle working fluid in a supercritical CO_2 turbine before being sent back to the reservoir.
Products	Geothermal energy for use in electricity generation
CO_2 utilisation per tonne of product output	Based on long term reservoir pressurisation/fluid loss studies-potential capability to continuously sequester 24 tonnes of CO_2 per day per MW_e by fluid diffusion into the rock mass surrounding the HDR reservoir. However, this will be site specific.
CO_2 source	CO_2 in a pure, dehydrated state (industrial grade), suitable for compression
Technology status (includes project status)	Status of EGS – Pilot projects are currently either operational or under development in Australia, the United States, and Germany. However EGS using supercritical CO_2 is at a very early stage of development and is yet to be tested at demonstration scale. (1) Joint venture of GreenFire Energy with Enhanced Oil Resources plan to build a 2MW CO_2 based demonstration plant near the Arizona-New Mexico border. Drilling of wells to access hot rock is proposed to commence in 2010. The proposed location is projected to yield enough heat to generate 800 MW of power with potential to absorb much of the CO_2 generated by six large coal-fired plants in the region. (2) Geodynamics Limited Innamincka 'Deeps' Joint Venture with Origin Energy: a 1 MW power plant has been constructed at Habanero. Electricity generation is expected to occur by early 2012 following the successful completion of Habanero 4 and Habanero 5 (reservoirs). This will be the first enhanced geothermal system in Australia. Due to make final investment decision on proposed $300 million, 25MW geothermal demonstration plant in the Cooper Basin by early 2013, after 12 months of successful operation of the Habanero closed loop. (This is two years later than previously stated). Testing the use of supercritical CO_2 as the working fluid in geothermal systems is projected to commence in 2013.
Funding/support	U.S. Department of Energy recent award of US$338 million in federal stimulus funds for geothermal energy research.

CRITERIA	DESCRIPTION
General benefits	The significant density difference between the cold $SCCO_2$ in the injection well and the hot $SCCO_2$ in the production wells provide a large buoyant drive (thermal siphoning) and markedly reduce the circulating pumping power requirements of a water-based Hot Dry Rock (HDR) system. Inability of $SCCO_2$ to dissolve and transport mineral species from the geothermal reservoir to the surface would eliminate scaling in the surface equipment (piping and heat exchangers). HDR reservoirs with temperatures > 375ºC (the critical temperature for water) could be developed without problems associated with silica dissolution. Much larger flow rates can be achieved with CO_2 than can be achieved with water due the lower viscosity of CO_2.
General barriers	EGS for power generation is still relatively novel technology and remains to be proved on a large scale. The lifetime of HDR geothermal system may be difficult to prove. There are a number of significant issues that need to be resolved. These include the geochemistry of supercritical CO_2, the corrosive conditions that arise with CO_2 in contact with reservoir water, and long term effects in terms of reservoir connectivity, the source of CO_2, the long term retention of CO_2, and design and optimisation of power generation systems to work with supercritical CO_2. CO_2 has a lower specific heat capacity than water, and so greater flows are required to achieve the same heat extraction. Potential barriers to implementation include access to CO_2 at an acceptable cost, proximity of the EGS to the electricity grid, and access to cooling water. Similar issues related to long term responsibility for the resultant reservoir, including the liability for future CO_2 leakage. There is concern in the Geothermal industry that carbon capture/CCS is a transitionary technology and availability of CO_2 in the very long term is raised as a concern.

Refer to Appendix C for further details of EGS technology using supercritical CO_2 as the working fluid.

2.4 CO_2 AS FEEDSTOCK FOR POLYMER PROCESSING

A new approach to polymer processing is to combine traditional feedstocks with CO_2 to synthesise polymers and high value chemicals. The technology transforms carbon dioxide into polycarbonates such as polypropylene carbonate and polyethylene carbonate, using a zinc-based catalyst in a reaction with epoxide molecules.

Table 2.4 Polymer processing summary

CRITERIA	DESCRIPTION
GENERAL DESCRIPTION	
Technology	CO_2 as feedstock for polymer production
Proponents	Novomer
Description	Novomer's technology uses carbon dioxide as a feedstock to synthesise chemicals and materials for a number of every day applications. The technology transforms carbon dioxide into polycarbonates using a proprietary zinc-based catalyst system. The chemicals and materials produced contain up to 50 per cent carbon dioxide or carbon monoxide.
Products	Polymer coatings, plastic bags, laminates / coatings, surfactants for EOR, automotive and medical components.
CO_2 utilisation per tonne of product output	Novomer's plastics are made from 50 per cent fossil fuels and 50 per cent CO_2. For each tonne of Novomer's plastics manufactured, up to one half tonne of CO_2 can be sequestered.
CO_2 source	CO_2 will be sourced from a waste stream, e.g. from ethanol fermentation, reformers, natural gas wells, flue gas from coal-fired power plants, etc. The CO_2 sourced from industrial emissions is likely to require some degree of purification.
Technology status (includes project status)	Novomer has been producing CO_2 based plastic material on a pilot scale at Kodak Speciality Chemicals facility in Rochester, NY, since December 2009. Pilot scale plant is based on a patented technology developed by Cornell University.
Funding/support	In March 2010, Novomer was awarded US$2.1 million in the first phase of a potential US$25 million federal stimulus grant for sustainable materials production from the U.S. Department of Energy (DOE). Novomer is preparing an application for a follow-on Phase two award for a 24-month, approximately US$23 million project. This is subject to further DOE evaluation and approval.
General benefits	The use of carbon dioxide and carbon monoxide as feedstock, instead of the corn-based feedstock used by other biodegradable plastics, means that the production of plastic will not compete with food production. Traditional chemical industry infrastructure can be used to manufacture the plastic.
General barriers	Technology is still at a relatively early stage – it has only been demonstrated at a small scale (using a batch reactor).

Refer to Appendix D for further details of using CO_2 as a feedstock for polymer production.

2.5 CO_2 FOR USE IN ALGAE CULTIVATION

The injection of CO_2 may improve the economics of algal growth systems, making it a potential volume user of concentrated CO_2 streams. As with CO_2 supplemented atmospheres in industrial greenhouses, bubbling CO_2 through algal cultivation systems can greatly increase productivity and yield (up to a saturation point). There is currently significant interest in the potential of algae to produce oil (mostly with a view to liquid transport fuel substitutes) at a price that is competitive with crude oil.

Figure 2.4 Algae cultivation overview

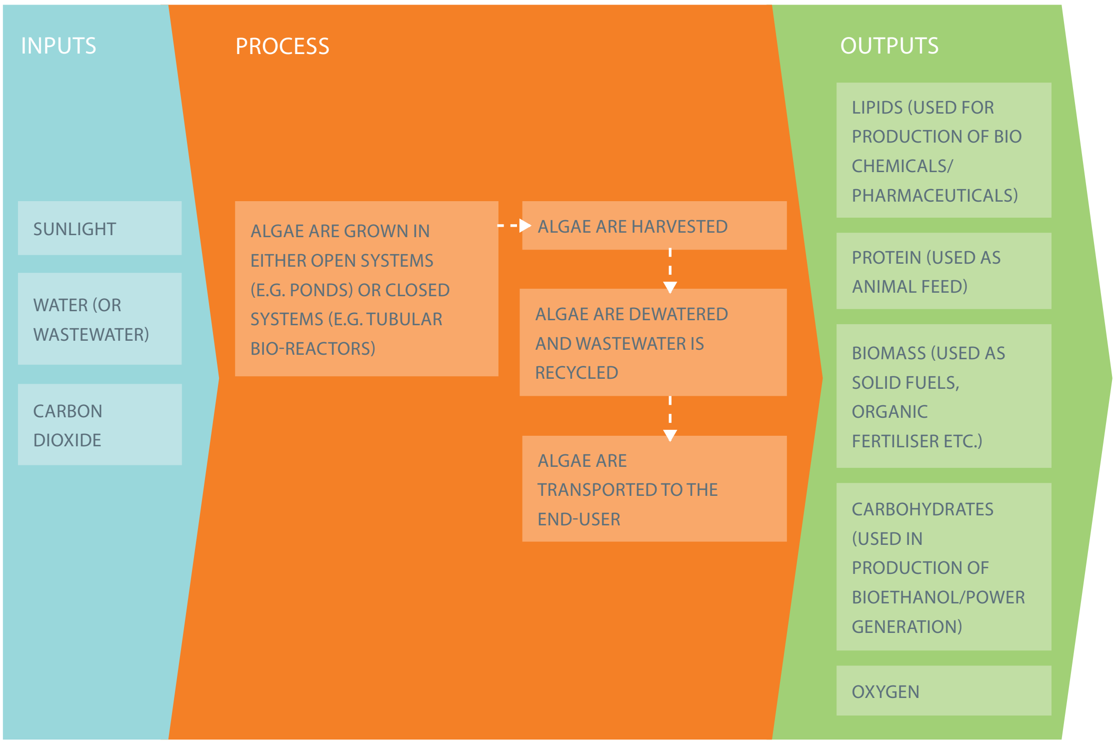


Table 2.5 Algae cultivation summary

CRITERIA	DESCRIPTION
GENERAL DESCRIPTION	
Technology	CO_2 absorption by microalgae to generate biomass.
Proponents	Algenol, US Solazyme, US MDB Energy, AU
Description	Bubbling CO_2 through algal cultivation systems can greatly increase production yields of algae. There has been significant interest in the last few decades in the potential of algae to produce oil at a price that is competitive with crude oil.

CRITERIA	DESCRIPTION
Products	The algal biomass produced can be processed in numerous ways to extract economic value, depending on the desired output product/s. Commonly, the natural oil fraction (some species are capable of producing 70%wt oil content) 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.
CO_2 utilisation per tonne of product output	Typically, ~1.8 tonnes of CO_2 will be utilised per tonne of algal biomass (dry) produced, though this varies with algae species.
CO_2 source	CO_2 used in algae cultivation can be taken from a range of sources. One of the main sources investigated for large-scale production is power plant flue gases. Algae cultivation systems are biological systems and so have sensitivities to certain components and impurities. The source CO_2 would typically go through some clean-up processes to remove any components, which may have a detrimental effect on the algae. Food grade CO_2 could be considered the ideal source.
Technology status (includes project status)	There are currently no closed algal cultivation systems for biomass/biofuel production operating on a large scale, though there are many around the world emerging at pilot or demonstration scale, and it is no longer just a laboratory experiment. Several large global companies including BP, Chevron, Virgin and Royal Dutch Shell have invested research funding into various systems and are currently carrying out feasibility studies.
Funding/support	Several multi-billion dollar programs now exist driven by oil majors, with large multi-disciplinary research collaborations now underway at a number of universities in the US, Australia, NZ, Japan, China, South Africa and Europe. Support has been granted by the Mexican government and Presidency, for the aforementioned project by Algenol and BioFields in the Sonora Desert.
General benefits	Has high potential for large scale reuse of CO_2 Algal oil can be injected into existing crude oil refineries. Use of algae derived energy carriers (biofuel, biogas) results in displacement of fossil equivalents.
General barriers	Capital intensity of cultivation systems is currently a limiting factor. Requires large amounts of nutrients similar to existing agricultural systems, most of which are currently CO_2 intensive in production, though in a captive system these can be managed more effectively and 'recycled'.

Refer to Appendix E for further details of algae cultivation using CO_2.

2.6 CO_2 AS FEEDSTOCK FOR CARBONATE MINERALISATION

Carbon mineralisation is the conversion of CO_2 to solid inorganic carbonates using chemical reactions. In this process, 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 or in natural brines, are chemically reacted with CO_2 to produce compounds such as magnesium carbonate ($MgCO_3$) and calcium carbonate ($CaCO_3$, commonly known as limestone). The carbonates that are produced are stable over long time scales and therefore can be used for construction, mine reclamation, or disposed of without the need for monitoring or the concern of potential CO_2 leaks that could pose safety or environmental risks.

Figure 2.5 Calera CMAP process overview

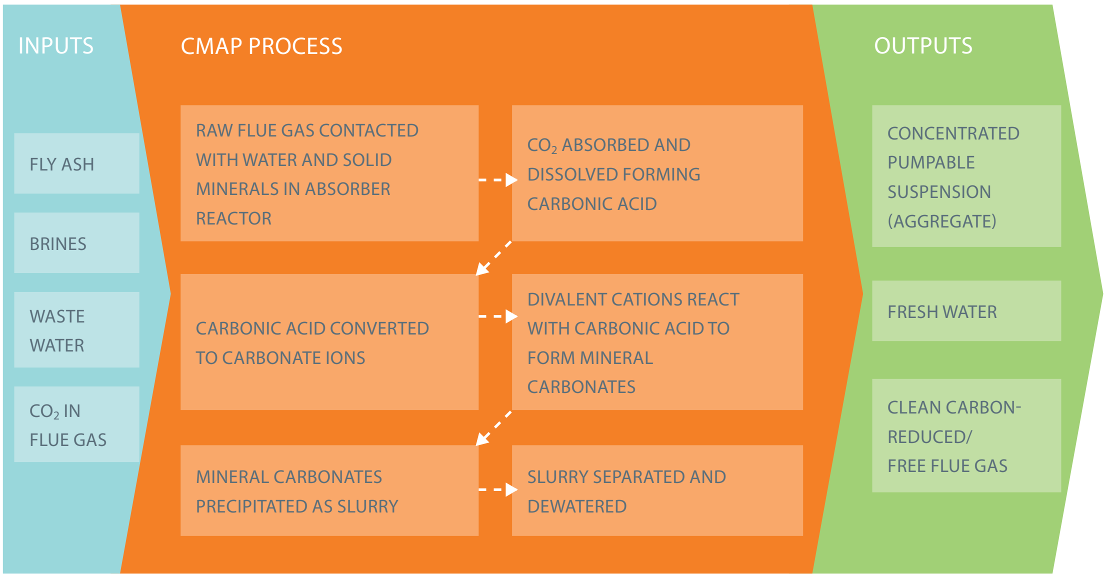


Table 2.6 Carbonate mineralisation technology summary

CRITERIA	DESCRIPTION
GENERAL DESCRIPTION	
Technology	1. Calera Process – carbonate mineralisation 2. Skymine technology The numbering scheme above will be retained throughout the table to differentiate between the two technologies.
Proponents	1. Calera 2. Skyonic Corporation (Texas)
Description	1. Moderately concentrated CO_2 (e.g. power station flue gas) is contacted with mineral-loaded alkaline brine. The CO_2 present in the gas precipitates out as mineral carbonates (limestone / dolomite equivalent precipitates). 2. Skyonic's SkyMine® technology removes CO_2 from industrial waste streams through co-generation of saleable carbonate and/or bicarbonate materials.
Products	1. Aggregate and supplementary cementitious material (SCM), which can be used to make concrete, asphalt, and other building applications. 2. The mineralised carbon dioxide (baking soda) will be used in several industrial applications and tested as feedstock for bio-algae fuels.
CO_2 utilisation per tonne of product output	1. Approx. 0.5t CO_2 per tonne of mineral carbonate produced 2. Not specified
CO_2 source	1. Relatively low concentration CO_2 source is required. Direct use of power station flue gas is possible. 2. Industrial waste streams, e.g. cement plants.

CRITERIA	DESCRIPTION
Technology status (includes project status)	1. Calera: Continuous pilot-scale plant operational – producing average 5t/day of SCM in Moss Landing California; Demonstration plant is under construction (will use a 10MW slipstream from the 1.5GW Dynergy Moss Landing gas-fired power plant). 2. Phase 1 of Capitol-SkyMine® demonstration facility has been initiated at Capitol Aggregates, Ltd cement plant in San Antonio, Texas, USA. (This includes modelling, simulation, design, costing, and procurement activities). Construction of a commercial-scale facility is anticipated by the third quarter of 2010. The Capitol-SkyMine® plant is targeted to capture 75,000 metric tonnes of CO_2 from flue gas and mineralise carbon emissions to produce 143,000 metric tonnes of baking soda.
Funding/support	1. Calera endorsed by the US DOE; 23 September 2009 and awarded a grant for the expansion of the Moss Landing facility to a demonstration scale. 2. Skyonic received a $3 million "Carbon Capture and Sequestration from Industrial Sources and Innovative Concepts for Beneficial CO_2 Use" grant administered by the Department of Energy and the National Energy Technology Laboratory (DOE/NETL). Private investors are contributing the balance of Phase I funds. In mid–2010, Skyonic will have the opportunity to apply for a Phase 2 grant from DOE/NETL to support plant construction.
General benefits	The Calera process has the following benefits: • One of the by products is fresh water that could be used as potable water, irrigation water, or an industrial water supply, which may alleviate the water deficit in some regions. • The process utilises fly ash and waste water. • The technology does not require CO_2 separation or compression. • SCM can enhance the strength of concrete and supplant a portion of the cement in concrete blends. Both the Calera process and Skymine technology have the following benefits: • Technology can be retrofitted to stationary emitters. • The process is scalable. • The process captures and/or removes other emissions including sulphur dioxide, particulate matter, mercury and other metals.
General barriers	General barriers to the Calera process: • The technology has the potential to be rejected by the cement industry (as it produces a product that is already produced in the manufacture of cement), and would require a carbon price as an incentive for cement manufacturers. • The success of the CMAP technology is highly dependent on the availability of suitable subsurface waters (brine) to provide the requisite hardness and alkalinity required and within abundant supply.

Refer to Appendix F for further details of using CO_2 as a feedstock for mineralisation.

2.7 CO_2 FOR USE IN CONCRETE CURING

Canadian company Carbon Sense Solutions Inc. (CSS) is seeking to use a point source of CO_2 to limit the need for heat and steam curing of precast concrete products. Instead of the traditional energy intensive steam curing technologies, the proposed CSS concrete curing process consumes carbon dioxide from onsite flue gases and local combustion sources to cure precast concrete products, with claimed equal material performance to the traditional curing process.

Table 2.7 CO_2 for use in concrete curing summary

CRITERIA	DESCRIPTION
GENERAL DESCRIPTION	
Technology	Concrete Curing
Proponents	Carbon Sense Solutions Inc. (CSS)
Description	Point source emission of CO_2 used to limit the need for heat and steam in the curing process in the production of precast concrete products.
Products	Precast concrete products.
CO_2 utilisation per tonne of product output	Estimated at less than 120kg CO_2/t precast concrete produced.
CO_2 source	CO_2 captured from industrial sources, ideally from sources within close proximity to the concrete plant.
Technology status (includes project status)	Technology is currently moving towards a small-scale demonstration. It remains to be proven.
Funding/support	No external funding or support received.
General benefits	Producers will benefit from energy and water reductions resulting in cost savings and efficiency gains. The proponent claims the process is easily retrofitted, requiring targeted modifications to existing plant machinery with minimal disruption to existing processes. It is also claimed that the use of CO_2 results in an accelerated curing process with lower temperatures required.
General barriers	The concrete sector operates within a highly competitive commodity market with limited capital to invest in new technologies. The change in production method (curing process) must not compromise material performance as the material performance is governed by industry standards (e.g. ASTM, CSA).

Refer to Appendix G for further details of using CO_2 for concrete curing.

2.8 CO_2 FOR USE IN BAUXITE RESIDUE CARBONATION

The extraction of alumina from bauxite ore results in a highly alkaline bauxite residue slurry (known as 'red mud'), with a pH of approximately 13. The bauxite residue contains a mixture of minerals and some alkaline liquor (NaOH) from the Bayer extraction process. At Kwinana in Western Australia, Alcoa operates a residue carbonation plant, where gaseous CO_2 from a nearby ammonia plant is contacted with the red mud slurry, reducing the pH of the slurry to a less hazardous level.

Figure 2.6 Bauxite residue carbonation overview

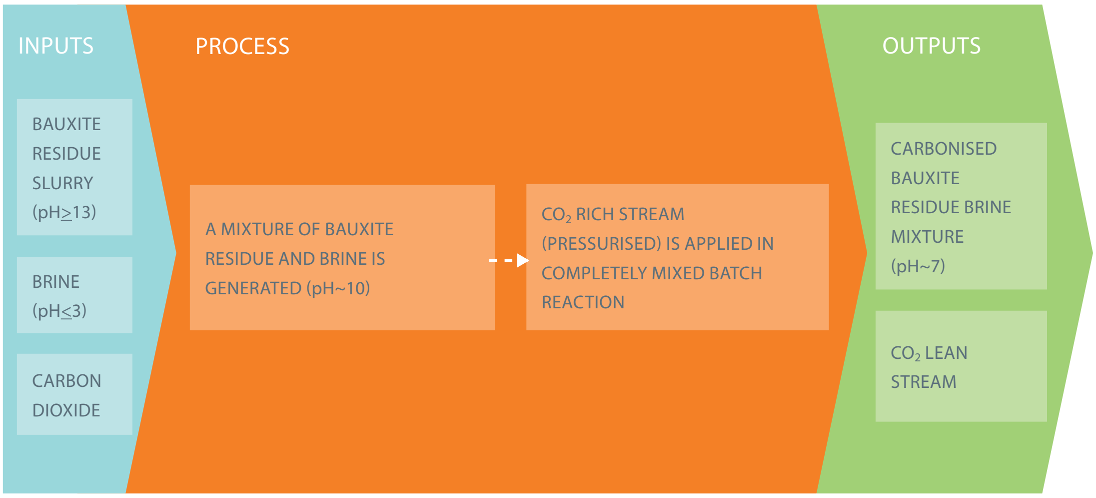


Table 2.8 Bauxite residue carbonation summary

CRITERIA	DESCRIPTION
GENERAL DESCRIPTION	
Technology	Bauxite residue carbonation
Proponents	Alcoa
Description	The extraction of alumina from bauxite ore results in a highly alkaline bauxite residue slurry known as 'red mud', which causes environmental and handling problems in disposal. Alcoa of Australia uses a stream of CO_2 from a nearby ammonia plant, contacting the CO_2 with the red mud slurry to reduce the pH of the slurry to a less hazardous level for easier handling. Note: Brine is not utilised in Alcoa's bauxite residue process.
Products	When alkalinity is neutralised sufficiently, the product can be used as aggregate material for mine reclamation / construction.
CO_2 utilisation per tonne of product output	Red mud treated with sea water has a large theoretical capacity to absorb CO_2 (up to 750kg CO_2 / t red mud). However, Alcoa only proposes a level of 30-35kg per tonne of red mud (dry weight), as this is what is required to convert all of the alkalinity to carbonates.
CO_2 source	At present, the process at Kwinana is only economical because of the availability of a low-cost source of high concentration CO_2 from the adjacent ammonia plant. Alcoa advises that they currently believe the system requires concentration above 85 per cent – the process requires the CO_2 to be in direct contact with the thickened slurry for reasonable holding time – a more dilute gas makes this difficult. An alternative process is proposed to utilise flue gas from captive power generation at Alumina refineries.

CRITERIA	DESCRIPTION
Technology status (includes project status)	Alcoa of Australia operates this process commercially at their Kwinana Alumina refinery, utilising a concentrated stream of CO_2 from an adjacent Ammonia Plant, which is transported 8km by pipeline to the residue carbonation plant. Alcoa's patents on the technology have expired, but they are offering other alumina producers a 'technology transfer' package that includes their more detailed intellectual property. Alcoa has also recently patented an integrated carbon capture and residue carbonation process that would allow the use of flue gas from captive power generation plant emissions.
Funding/support	No external funding or support received so far.
General benefits	Improves the handling and dusting characteristics of red mud, and reduces the costs of its disposal. Potential for use of the carbonated red mud as a soil amendment for acidic soils (see also http://www.csrp.com.au/projects/alkaloam.html).
General barriers	The prospects for implementation are restricted to alumina refineries with ready access to high concentration CO_2 sources, and the scale of potential application is restricted by the limited prospects of material product revenue generation and by the relatively low levels of storage per tonne of bauxite residue.

Refer to Appendix H for further details of using CO_2 for neutralising bauxite processing residues.

2.9 CO_2 AS A FEEDSTOCK FOR LIQUID FUEL PRODUCTION

CO_2 as a feedstock for liquid fuel production is a broad category for CO_2 reuse, which includes conversion of CO_2 to a number of alternative fuel products, including formic acid, methanol, dimethyl-ether, ethanol, and other petroleum equivalent products. To produce these varied end products, a range of CO_2 conversion technologies are proposed.

In general, the primary energy input for these conversion technologies is renewable energy, with the current proponents focused on solar and geothermal energy. This is an important requirement for these technologies, as generally they have relatively low thermal efficiency (e.g. relatively small fraction of the energy input is converted to useful fuel). It should be noted that only renewable methanol production and formic acid production (as a hydrogen energy carrier) have been evaluated in detail in the current exercise, predominantly due to a lack of publicly available information for the other proposed technologies.

Figure 2.7 Renewable methanol production overview

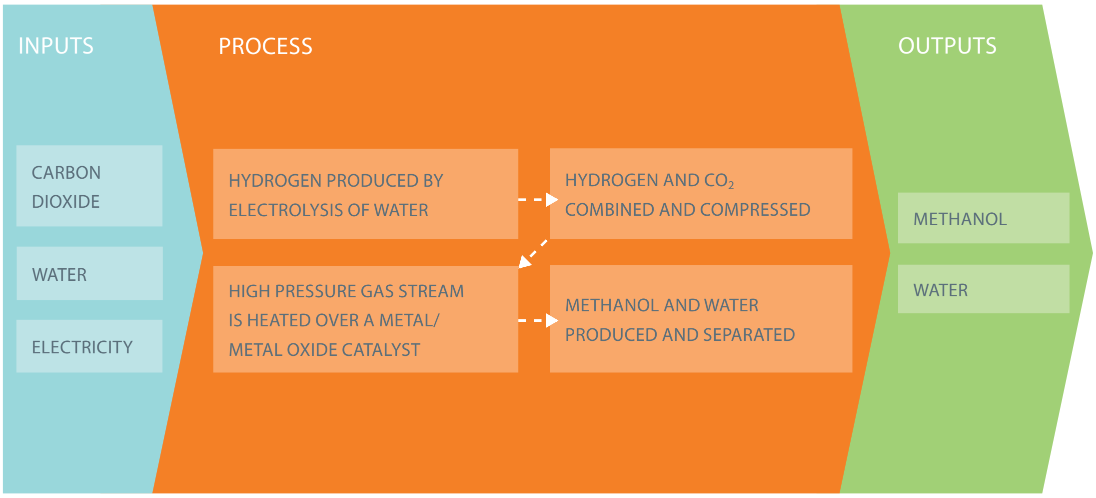


Figure 2.8 Formic acid production overview

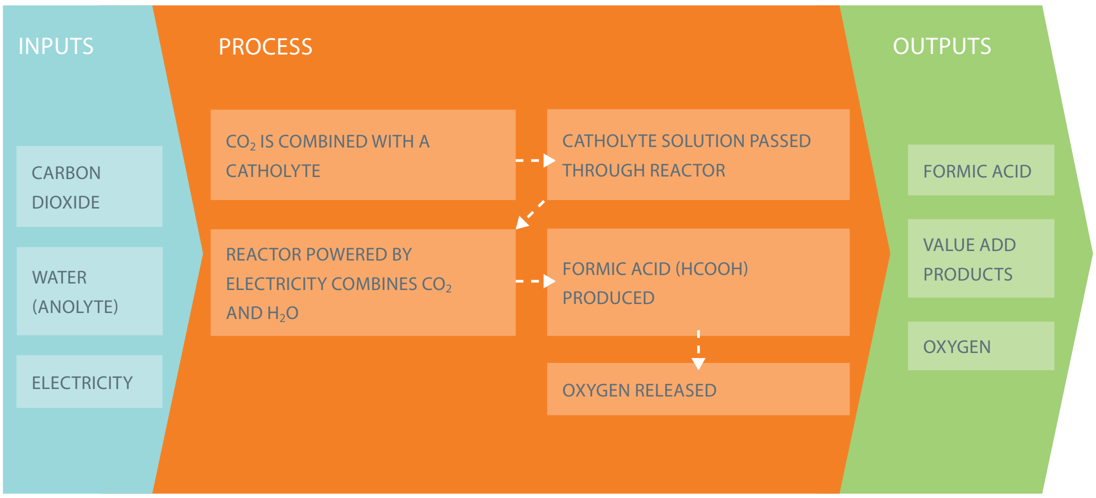


Table 2.9 Liquid fuel production summary

CRITERIA	DESCRIPTION
GENERAL DESCRIPTION	
Technology	CO_2 to Liquid Fuels A range of technologies fall under the category of CO_2 to liquid fuels technologies, and these are at varying stages of development. These technologies typically require renewable or zero-emissions energy inputs in order to achieve reduced CO_2 emissions relative to fossil fuels. More developed technologies include: 1. renewable methanol (electrolysis of water to produce H_2, subsequent catalytic conversion of H_2 and CO_2 to methanol); and 2. formic acid as a hydrogen energy carrier (electro-reduction of CO_2 in H_2O). Less developed technologies include: 3. hydrocarbon excreting micro-organisms (helioculture); 4. bio/organo-catalysts for direct bio-production of hydrocarbons; 5. Counter Rotating Ring Receiver Reactor Recuperator (CR5) – high temperature process with metal oxide catalyst; 6. semiconductors; and 7. titanium dioxide nanotube catalyst / other nanomaterial catalysts. The above numbering scheme will be retained throughout the table.
Proponents	1. Carbon Recycling International (CRI) 2. Mantra Venture Group (Mantra) 3. Joule Unlimited Inc 4. Carbon Sciences 5. Sandia National Laboratories 6. University of California 7. Pennsylvania State University

CRITERIA	DESCRIPTION
Description	1. Electrolysis of water to produce H_2. H_2 and CO_2 are combined, compressed and reacted over a catalyst at moderate temperature and pressure (~5MPa, ~225ºC) to produce methanol and water. 2. Electro-reduction of CO_2 to produce formic acid (HCOOH) and O_2. Formic acid is used as a hydrogen carrier, with hydrogen the primary fuel (classified as a liquid fuel as hydrogen is only released from the liquid formic acid as required). Energy input = electricity at 8MWh/t CO_2. 3. Engineered product-specific photosynthetic organisms circulate in a solution of micronutrients and brackish water, producing hydrocarbon products as a by-product of metabolism. Energy input is direct, unconcentrated solar energy. 4. Bio/organo-catalysted conversion of CO_2 and H_2O to light hydrocarbons with low pressure, low temperature energy input; energy input not further described; light fraction hydrocarbons can then be further processed into the desired product. 5. High temperature solar concentrator provides heat for chemical splitting of CO_2 and H_2O into CO, H_2 and O_2, and catalysed by a metal oxide; CO and H_2 together provide a syngas that can be transformed into multiple hydrocarbon products using the Fischer Tropsch process. 6. Gallium-phosphide semiconductor is combined with two thin sheets of nickel-based catalysts; CO_2 is split directly into CO and O_2; energy input is from direct, unconcentrated sunlight. 7. TiO_2 catalysed conversion of CO_2 and H_2O to methane and other compounds; energised by direct, unconcentrated sunlight.
Products	1. Methanol 2. Formic acid (hydrogen carrier) 3. Ethanol and diesel equivalent products 4. Gasoline and diesel equivalent products 5. Syngas for further conversion to liquid fuels 6. Syngas for further conversion to liquid fuels 7. Methane and other light hydrocarbon products with potential for further processing to liquid fuels
CO_2 utilisation per tonne of product output	Assuming a gasoline-equivalent product, CO_2 utilisation would be approximately 3.1 metric tonnes per tonne of liquid fuel.
CO_2 source	Flue gas from power plants and other industrial sources

CRITERIA	DESCRIPTION
Technology status (includes project status)	1. Constructing first commercial demonstration in Iceland. 2. In negotiations for first commercial demonstration (to be located in Korea). 3. Moving from laboratory towards commercial demonstration. 4. Start-up, publicly listed company – no active projects listed. 5. Prototype device constructed; Researchers hope to achieve a solar energy conversion efficiency of a few per cent (photosynthesis is approximately 1 per cent). 6. Laboratory demonstration, commercial viability not discussed. 7. Laboratory demonstration, commercial viability not discussed.
Funding/support	1. Investors and partners identified include: Iceland Oil (Ollis) – methanol customer; HS Orka – geothermal developer and CO_2 feedstock provider; Innovation Center Iceland – national laboratory under the Ministry of Industry potentially providing grants and technology development assistance; and Century Aluminium as an industrial research partner. Degree of investment by each of the above parties is unknown. 2. The National Research Council of Canada Industrial Research Assistance Program (NRC-IRAP) has agreed to fund 50 per cent of the costs associated with the development of Mantra's ERC technology.
General benefits	CO_2 is essentially an energy carrier – the energy input can be from renewable or low emissions sources.
General barriers	Low efficiency (typically). High capital cost (anticipated based on technology descriptions available). Main application would be for transportation fuels. However, alternative transport systems (such as electric vehicles with regenerative braking coupled to a renewable energy powered electricity grid) may be a more competitive solution, with significantly higher overall energy conversion efficiency.

Refer to Appendix I for further details of utilising CO_2 as a feedstock for liquid fuel production.

2.10 CO_2 FOR USE IN ENHANCED COAL BED METHANE RECOVERY (ECBM)

Coal bed methane is a useful source of energy and is increasingly extracted and used to supplement conventional natural gas supply. Normally, extraction is achieved by drilling wells into, and below, deep un-minable coal seams, and pumping out the water which naturally saturates the seam. This has the effect of reducing the hydrostatic pressure and causes the gas to be released from the coal. The gas is separated from the water at the surface, after which time, it can be utilised in the same applications as conventional natural gas.

In principle, the production of coal bed methane can be enhanced by injecting CO_2 into the partially depleted coal seam where it is preferentially adsorbed into the coal, thereby displacing methane, which is released as further production to the surface. In practice however, the adsorption into the coal of

CO_2 causes it to expand and close up the fissures that provide the pathways and permeability for both gas production and gas injection. The benefits that arise from CO_2 injection, of flushing out residual methane from the coal, may therefore be progressively offset by a reduction in permeability that inhibits methane production and CO_2 injection. Further research and trials are required to establish whether and how ECBM can be developed so that the benefits decisively outweigh the offsets.

Table 2.10 Enhanced coal bed methane recovery summary

CRITERIA	DESCRIPTION
GENERAL DESCRIPTION	
Technology	Enhanced coal bed methane
Proponents	Interest in CO_2 ECBM is focused on developed economies with large coal reserves, such as the US, Europe, Canada, Australia and New Zealand and where there is funding to support development of the technology. Research is being undertaken by these countries' scientific organisations, including CSIRO, NETL, AITF, and JCOAL amongst others. China United Coal Bed Methane Corporation is involved in several research/ demonstration projects. In the US, Consol Energy operates a pilot injection project funded by the US DOE.
Description	ECBM involves flooding coal seams with injected CO_2, where it's adsorbed by coal, in turn displacing methane to the surface for it to be captured and consumed as fuel.
Products	Natural Gas (Methane).
CO_2 utilisation per tonne of product output	CO_2 injection per gas displacement rate is very dependent on the reservoir's characteristics (e.g. size, pressure, temperature). A study carried out in Alberta, Canada, found the injection recovery rate for CO_2 to CH_4 is 2:1 on a volume basis. As stated, this could vary dramatically and would need to be examined on a site by site basis.
CO_2 source	Naturally occurring CO_2 reservoirs and CO_2 captured from industrial sources.
Technology status (includes project status)	ECBM recovery is a developing technology, to date trialled on a pilot scale.
Funding/support	A number of countries with large coal resources are investigating the potential of ECBM and are funding research to better understand the process and to overcome the constraints on injectivity. Developing countries with growing energy demands and large coal resources, like China and Indonesia, are also investigating ECBM potential.
General benefits	Increased natural gas revenue through CO_2 storage. Return on investment through natural gas production could assist industrial CCS roll-out in the short term. Permanent storage of CO_2 once injected in a coal seam.
General barriers	The technology is at an early stage of development. It is not yet clear whether and how its theoretical methane displacement benefits can decisively outweigh the permeability deterioration offset that accompanies CO_2 injection.

Refer to Appendix J for further details of using CO_2 for Enhanced Coal Bed Methane Recovery (ECBM).

3. TECHNOLOGY CATEGORISATION

Not all CO_2 reuse technologies require a concentrated stream of CO_2. Some technologies could utilise a dilute stream of CO_2 (e.g. flue gas) and hence would not require a conventional capture plant. Furthermore not all technologies permanently store CO_2. These attributes will lead to different effects when considering the objective of accelerating the uptake of CCS.

It is evident from the detailed investigation in Section 2 that the short-listed reuse technologies utilise varying sources of CO_2 (from a concentrated stream of CO_2 to a dilute stream of CO_2 such as untreated flue gas) and also have varying abilities to permanently store CO_2. The differentiation of these attributes is important as they will have a different impact on the objective of accelerating the uptake of CCS.

CO_2 reuse technologies which require conventional capture plants may contribute cost reductions in capture plant from capability building, learning and knowledge sharing. However reuse technologies that utilise flue gas directly might provide a lower cost option for capturing CO_2, and provide some form of revenue. Consequently they have potential to act as a transitional measure to conventional CCS, (for example if there are delays in developing integrated CCS projects due to the timing of access to viable storage sites).

Generally reuse technologies that do not provide permanent storage are likely to be exposed to risk due to the uncertainty around the carbon price liability (where a carbon price is present). This is explained in more detail in Part 2 – Section 4 of the report.

This section highlights the key differences between the reuse technologies and categorises them based on (1) CO_2 feedstock and (2) permanence of CO_2 storage.

3.1 CO_2 FEEDSTOCK

Carbonate mineralisation, concrete curing, algae cultivation and potentially ECBM could utilise flue gas directly and therefore would not require a conventional capture plant to deliver a concentrated CO_2 stream.

Reuse technologies that require a concentrated stream of CO_2 require a source, such as natural gas processing, from which concentrated CO_2 is a by-product, or the addition of a conventional capture plant to concentrate dilute CO_2 emission streams from sources such as power, steel and cement plants. Reuse technologies that utilise flue gas directly from dilute sources however, do not require conventional capture plant, and may need no more than some lower cost form of gas clean-up treatment.

Figure 3.1 presents the reuse technologies that require concentrated CO_2 and those that can utilise dilute CO_2 in flue gas directly or a low cost form of capture or treatment.

Figure 3.1 Technologies operating on concentrated CO_2 versus dilute CO_2

Operate on concentrated CO_2

- Enhanced oil recovery
- Fertiliser –urea yield boosting
- Enhanced geothermal systems
- Polymer processing
- Bauxite residue carbonation
- Renewable methanol
- Formic acid
- Enhanced coal bed methane

Operate on dilute CO_2

- Algae cultivation
- Mineral carbonation
- Concrete curing
- Enhanced coal bed methane

*ECBM – both CO_2 and direct flue gas ECBM is being considered.

In considering how reuse technologies can help to accelerate the uptake of CCS, the two categories above will have a different impact. Implementing reuse technologies that operate on a concentrated CO_2 stream and require a conventional capture plant to concentrate the stream may contribute to capability building, learning, and knowledge sharing, with some subsequent impact on cost reductions for conventional capture plants.

Implementing reuse technologies that use a diluted CO_2 stream, such as flue gas will not contribute to the development of conventional capture technology. However, these technologies could have potential for lower costs, enabling them to act as a transitional measure to conventional CCS (for example if there are delays in developing integrated CCS projects due to delays in access to viable storage sites). This issue is discussed further in Part 2 – Section 4 of this report.

There are differing purity requirements amongst the uses for CO_2 that require a relatively concentrated CO_2 stream. CO_2 for human consumption is typically a minimum of 99.8 per cent CO_2, with limits imposed on the nature of the allowable impurities. Chemical processes using CO_2 as a feedstock also tend to require an almost pure CO_2 stream, with specifications of 99.9 per cent + CO_2 not uncommon. EOR tends to have less stringent requirements, and 95 per cent CO_2 is a commonly accepted purity level. These differing purity requirements will inevitably have some cost implications for the final CO_2 product, but the market prices receivable for bulk gaseous CO_2 will remain low, as discussed in Part 2 of this report.

3.2 PERMANENCE OF CO_2 STORAGE

Reuse technologies that permanently store CO_2 are considered to be an alternative form of CCS and hence are referred to as 'alternative CCS'.

EOR, ECBM, EGS, carbonate mineralisation, concrete curing, bauxite residue carbonation and potentially algae cultivation (depending on the end product) are considered to be alternative forms of CCS.

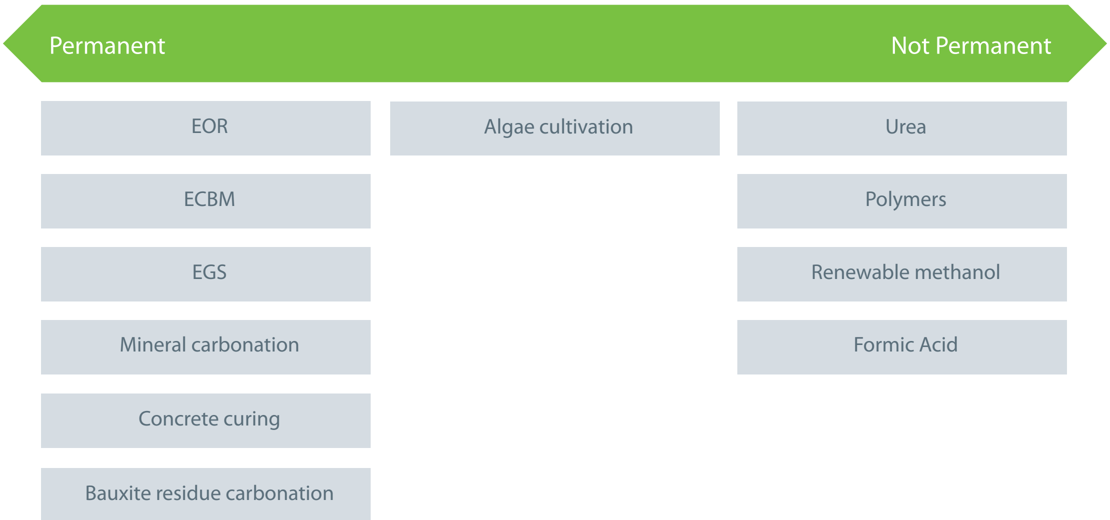
The reuse technologies' ability to permanently store CO_2 is another important attribute which is likely to have an impact on the viability of the technology and its ability to accelerate the uptake of CCS.

Some reuse technologies result in permanent storage of CO_2 considered suitable for hundreds to thousands of years (such as mineralisation). Urea fertiliser and polymers may start to breakdown and release CO_2 from one to six months after use, while products such as fuels will release CO_2 once utilised (combusted) releasing CO_2 back into the atmosphere.

Reuse technologies which permanently store CO_2 are considered to be an alternative form of CCS and may be referred to as 'alternative CCS' throughout the report.

Figure 3.2 shows the reuse technologies and their ability to store CO_2 in the derived end product.

Figure 3.2 Permanent versus non-permanent storage



Note: Algae cultivation can result in various products, which may result in semi-permanent and non permanent storage of CO_2. While the production of biofuels through algae cultivation does not permanently store the CO_2, it may have an equivalent mitigation effect where the algal biofuels effectively replace fossil fuels.

The two permanency categories above will have a different impact when considering how reuse technologies can help to accelerate the uptake of CCS. Implementing reuse technologies that also provide permanent storage of CO_2 may avoid any carbon price implications. Reuse technologies which do not permanently store CO_2 are exposed to greater risk due to the uncertainty of the carbon price liability between emitter and end product, which could affect the commercial viability of the technology or the competitiveness of the end product. This is discussed further in Part 2 – Section 4 of the report.

3.3 TECHNOLOGY CATEGORISATION

Section 3.1 highlighted that not all of the short-listed reuse technologies require a concentrated stream of CO_2 while section 3.2 indicates that not all technologies result in permanent storage of CO_2. Considering both of these attributes together the reuse technologies fall into the following four categories:

1. Reuse technologies which require concentrated CO_2 (and a conventional capture plant for power, steel and cement sources) and permanently store CO_2.

2. Reuse technologies which require concentrated CO_2 (and a conventional capture plant for power, steel and cement sources) and do not permanently store CO_2.
3. Reuse technologies which do not require concentrated CO_2 (or a capture plant) and permanently store CO_2.
4. Reuse technologies which do not require concentrated CO_2 (or a capture plant) and do not permanently store CO_2.

Figure 3.3 presents the short-listed technologies into the four categories as outlined above.

Figure 3.3 Technology categorisation

CO_2 Feedstock \ CO_2 Storage	Permanent	Not Permanent
Captured high concentration CO_2	EOR ECBM EGS Bauxite residue	Urea Polymers Renewable methanol Formic acid
Dilute CO_2 flue gas	ECBM Mineral carbonation Concrete curing Algae cultivation	Algae cultivation

This categorisation is important in the overall assessment and evaluation of reuse technologies and their ability to accelerate the uptake of CCS. This is discussed further in Part 2 – Section 4 of the report.

4. TECHNOLOGY COMPARISON

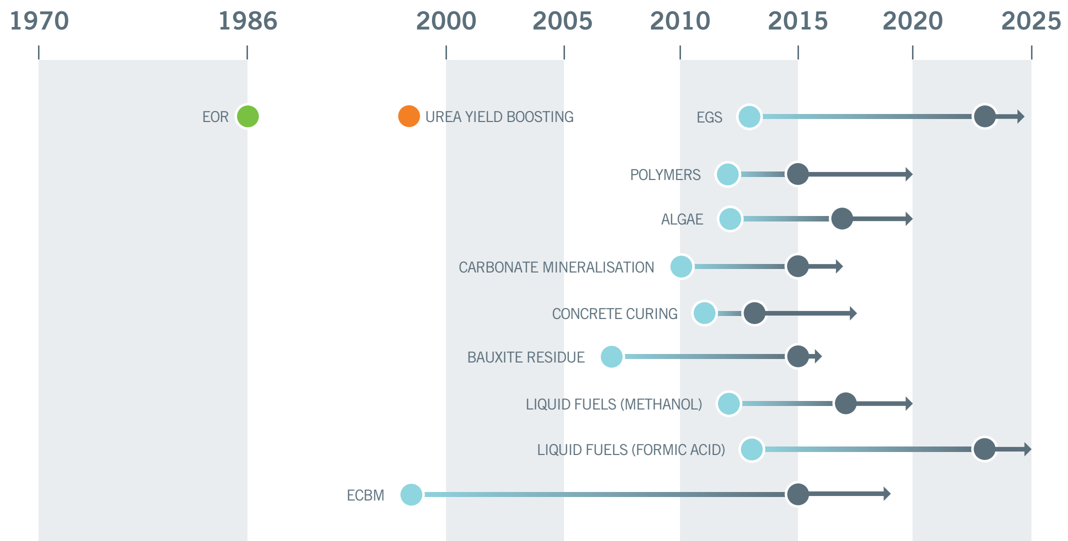
This section undertakes a high level comparison of the short-listed CO_2 reuse technologies focusing on key criteria such as technology maturity, potential revenue generation, level of investment to achieve commercialisation, CO_2 emissions from reuse, and the applicability of short-listed technologies to developing countries.

4.1 MATURITY OF REUSE TECHNOLOGIES

The short-listed technologies are at varying stages of development and maturity. EOR and urea yield boosting are mature technologies already in commercial use. Bauxite residue carbonation and renewable methanol are considered to be promising technologies ready for commercialisation. However the remainder (and the majority) of the reuse technologies are considered to be promising technologies at a conceptual stage that need to be proven further through technical pilots and/or demonstration plants.

The short-listed CO_2 reuse technologies are at varying stages of development and maturity. Figure 4.1 below provides an indication of the relative timeframe for demonstration and commercial operation of each of the CO_2 reuse technologies. The dates and timeframes presented are purely an indication based on claims from the respective proponents, and consequently the predictions may be optimistic.

Figure 4.1 Technology development timeline



Note 1: The light blue circle represents the technology at demonstration scale, while the dark blue circle represents commercial operation of the technology based on claims from the respective proponents. The arrow extending from the dark blue circle indicates a more pragmatic timeframe to commercialisation.

Note 2: Respective proponents for each technology are as follows: EGS – Geodynamics; Polymers – Novomer Ltd; Algae – MBD and Algenol; Carbonate mineralisation – Calera; Concrete curing – Carbon Sense Solutions; Bauxite residue – Alcoa; Liquid fuels (methanol) – Carbon Recycling International; Liquid fuels (formic acid) – Mantra; ECBM – China United Coal Bed Methane Corporation Ltd.

Note 3: Commercial operation of conventional urea production became commercial in 1970. Non-captive CO_2 capture for urea yield boosting became commercial in the late 1990's.

Only two of the short-listed technologies are already commercially viable and technologically mature (e.g. EOR and urea yield boosting). The majority of technologies are targeting demonstration before 2015; however the target for commercial operation is varied, ranging from 2013 to 2023. On this basis it is appropriate to further classify the technologies according to maturity in order to determine those which would benefit most from development and support in the near-term.

The short-listed technologies considered in the evaluation, fall into the three broad categories as indicated in Table 4.1 below.

Table 4.1 Technology maturity

A – MATURE TECHNOLOGIES ALREADY IN COMMERCIAL USE	B – PROMISING TECHNOLOGIES READY FOR COMMERCIALISATION	C – PROMISING TECHNOLOGIES AT A CONCEPTUAL STAGE THAT NEED TO BE PROVEN FURTHER THROUGH TECHNICAL PILOTS AND/OR DEMONSTRATION PLANTS
EOR	Bauxite residue (red mud) carbonation	Mineral carbonation
Urea yield boosting	Renewable methanol	Concrete curing
		ECBM
		EGS
		Polymers
		Algae
		Formic acid

Falling within category A, both EOR and urea yield boosting are proven technologies which are well understood and can be considered to be mature. Although these technologies are already applied on a large scale, they still have potential for significant growth in the short term, and as such they warrant consideration as a potential market for captured CO_2.

In category B, there are only two technologies that are ready for commercialisation; bauxite residue carbonation and renewable methanol. Both of these technologies are already in operation or soon to be operating at commercial demonstration scale as follows:

- The reuse of CO_2 to neutralise the waste bauxite residue is in operation at Alcoa's Kwinana Alumina refinery in Australia. There is potential for this to be rolled out across all of Alumina refineries with ready access to CO_2.
- Renewable methanol technology is progressing with CRI currently constructing a five million litre per annum commercial demonstration plant in Iceland. Methanol will be blended with conventional unleaded petrol and sold at Olis gasoline stations throughout the greater Reykjavik area.

The majority of the CO_2 reuse technologies fall into the final category C. Carbonate mineralisation, concrete curing, ECBM, EGS, polymers, algae cultivation and formic acid are all promising CO_2 reuse technologies which are at a conceptual stage and still need to be proven by pilot scale plants and/or tested further by demonstration plants. Some of the technologies are more advanced than others. In relative order of advancement the status of each of these technologies is highlighted below:

- The Calera process for carbonate mineralisation is expected to start construction on a demonstration plant in the Latrobe Valley, Victoria, Australia during 2010 with intentions to rapidly expand the plant to commercial scale following the initial demonstration phase. Even though the demonstration plant is not in operation it has been indicated that the process is thought to become commercial in less than five years, based on a rapid and relatively simple scale-up. However, project economics may hinge on the availability of a suitably large natural alkaline brine resource. Skyonic Corporation is also involved in carbonate mineralisation and has stated an intention to start construction of a commercial-scale facility by the end of 2010.
- The use of CO_2 to reduce the demand of heat and steam for concrete curing of precast concrete blocks has the potential to become commercial in less than five years. This is based on plans for a demonstration plant in 2011 and commercialisation in 2012. The transition between demonstration and commercial scale is rapid due to the limited modifications involved in retrofitting the existing precast concrete plants. The technology remains to be proven however, and uptake will depend on concrete industry acceptance.
- CO_2 use for ECBM is a relatively new technology and is still in the development phase. The impact of CO_2 injection on coal permeability remains a challenge. Research in the western world continues through government funding. As for the developing countries, China holds the main interest in this technology due to their large coal reserves and high dependence on coal power plants. Although ECBM-CO_2 has operated at a pilot scale demonstration from 1995 (as indicated in Figure 4.1), injecting initially around 100,000tpa equivalent, the timeframe to commercial deployment is considered a minimum of 5 years away. If the permeability challenge can be overcome there may be potential for this time frame to be accelerated in the event of increased natural gas prices.
- The use of CO_2 as a feedstock for the manufacture of polycarbonates is being advanced by Novomer Ltd. Testing has been completed at pilot and batch scale only at Kodak Speciality Chemicals facility in Rochester, NY, and Novomer are currently investigating continuous processing. The polymers are being tested in parallel in a range of conversion processes that include thin film extrusion to blow moulding. Materials produced are being offered to potential customers for testing.
- Although large scale open algal systems exist, the use of CO_2 to enhance growth is not common practice within the algae industry. Furthermore, the majority of open algal systems operating today typically produce high value nutraceuticals rather than energy products (e.g. transport fuel). There are many technological and operational issues to be addressed before a robust large scale system can produce oil at a price competitive with crude oil. Despite claims of some firms, most proponents of the technology agree that there is great potential but the technology is still at least 5–10 years away from commercial realisation.
- EGS technology using CO_2 as the working fluid is unlikely to be commercialised within the next 10 years as EGS itself (using water as the working fluid) is a relatively novel technology with as little as ten projects worldwide (with half of these in the R&D and demonstration stage). There are a number of significant issues that need to be resolved in order to use CO_2 as the working fluid. Testing of supercritical CO_2 as the working fluid in geothermal systems is not projected to commence until at least 2013.

- Mantra claims to be close to commencing an ERC demonstration project in South Korea to convert CO_2 to formic acid, however, there is no evidence of proponents developing the formic acid to H_2 part of the chain. It has been demonstrated (using for example a ruthenium catalyst and an aqueous solution of formic acid) by several research teams. It could be pursued commercially in the future should the CO_2 to formic acid part of the chain prove successful.

Amongst the seven short-listed CO_2 reuse technologies that fall within Category C, several have the potential to be ready for commercial deployment within five years and therefore warrant consideration as a potential market for captured CO_2. However, commercialisation of the use of CO_2 in enhanced geothermal systems is at least 10 years away, as is commercial use of formic acid in the context of use as a hydrogen (fuel) carrier, since the hydrogen recovery part of the chain remains relatively undeveloped.

4.2 POTENTIAL REVENUE GENERATION

Investigation indicates that EOR cumulative demand and associated gross revenue to 2020 by far exceeds the demand and revenue of all the other CO_2 reuse technologies.

As discussed in part 2 of this report the prospective surplus supply of high concentration CO_2 in most parts of the world will mean that the bulk CO_2 market will develop as a buyers' market, and average prices will remain modest and subject to downward pressure as and where carbon pricing regimes are strengthened. To give an indication of market value, current prices for high concentration gaseous CO_2 (from ammonia plants in the US) range between US$3 and US$15/metric tonne.

The upper range of revenue received for a tonne of bulk gaseous CO_2 in the near-term is likely to be of this order of magnitude, with lower prices in the longer term assuming carbon pricing is introduced more widely over time in industrialised economies. The total revenue that any particular CO_2 reuse technology may deliver is primarily a question of scale. The technology with the greatest cumulative demand is likely to provide the greatest gross revenue from the sale of CO_2 for reuse (before costs are considered).

In order to achieve a high level of cumulative demand before 2020 the CO_2 reuse technologies should offer:

- Maturity – technologies that are already commercially implemented will have immediate demand, and if the market for that technology is growing, demand can also grow (for example, EOR).
- Scale-up potential – technologies producing products in inherently high volume markets are likely to have greater demand for CO_2.
- Commercial viability – the more commercially attractive a technology is, the greater the uptake and subsequent demand can be expected.

The cumulative demand that each reuse technology could provide for anthropogenic CO_2 up to 2020 was estimated, based on the development schedules proposed by the respective project proponents. These market demand and related revenue estimates are shown in Table 4.2.

Table 4.2 Potential cumulative demand and gross revenue estimates for reuse technologies to 2020

CUMULATIVE DEMAND FOR CO_2 TO 2020	GROSS REVENUE TO 2020*	TECHNOLOGY/APPLICATION
>500Mt	>$7500M	EOR
20Mt to 100Mt	Up to $1500M	Urea, mineral carbonation and ECBM
5Mt to 20Mt	Up to $300M	Polymers, renewable methanol, CO_2 concrete curing, bauxite residue carbonation and algae cultivation
<5Mt	Less than $75M	Formic Acid and EGS

*Revenues based on an assumed bulk CO_2 price of US$15/tonne

4.3 LEVEL OF INVESTMENT

The level of investment required to advance the short-listed CO_2 reuse technologies to demonstration scale or commercial operation varies significantly from millions to billions of dollars. Publicly available information regarding the level of investment required is limited.

The short-listed CO_2 reuse technologies are at a varying stage of development and maturity and hence the level of investment required to advance the technologies to demonstration scale or commercial operation will vary significantly. An indication of the level of investment required for each reuse technology is outlined below.

EOR

A large amount of investment may be required to advance and further commercialise the technology outside of North America. The CENS project model, which is looking at the feasibility of using CO_2-EOR technology offshore in the North Sea, shows investment costs of roughly US$1.7 billion for CO_2 pipeline, US$2.2 billion for CO_2 capture plants and US$5.0 billion for EOR investment in oilfields (Sharman 2004). Conversely however, the investment required for onshore deployment of EOR in emerging economies such as China could be less than that of an equivalent development in North America.

UREA YIELD BOOSTING

MHI (Mitsubishi Heavy Industries) Ltd's project in the UAE uses CO_2 from flue gas emitted during the urea fertiliser production process as feedstock for urea synthesis and is estimated to cost US$1.2–1.5bn. This includes building a 2,000-tonne-a-day (t/d) ammonia plant and a 3,500-t/d urea train alongside Fertil's existing complex. Further details about the ongoing carbon capture and operating costs are not available.

EGS

A report by the Massachusetts Institute of Technology states that with a modest R&D investment of $1 billion over 15 years (or the cost of one coal power plant), could provide the platform for the deployment of 100 GWe (gigawatts of electricity) or more of EGS by 2050 in the United States. Whether this would utilise CO_2 as a heat transfer fluid is a separate question entirely.

POLYMERS

There is currently no publicly available information about the costs and investment requirements for implementation of the technology.

ALGAE

The use of recycled CO_2 for algae cultivation is still in the early research and development stages. There are currently no large scale algae cultivation projects in operation and the commercialisation of the technology is likely to require significant investment.

CARBONATE MINERALISATION

Calera are currently building a facility, Calera Yallourn, in the Latrobe Valley, Australia, which following a demonstration phase will be the first commercial-scale facility capable of capturing 200MW_e of CO_2. The CO_2 will be captured from the flue gas of a local coal power station. Calera have estimated that the costs associated with the facility include CAPEX requirement (including CO_2 capture and building materials) of US$300-380m and a cost of CO_2 capture of US$45-60/tonne of CO_2. Details of further operating and maintenance costs are not available.

CONCRETE CURING

There is currently limited information available about the costs and level of investment required to advance this technology.

BAUXITE RESIDUE

This process is already operating commercially at Alcoa of Australia, which utilises a low-cost source of high concentration CO_2 from the adjacent ammonia plant. Alcoa have advised that the system requires concentration above 85 per cent. An alternative process is proposed to utilise flue gas from captive power generation at Alumina refineries, whereby the level of investment required will be based on the capture plant required to achieve concentrations above 85 per cent and any associated pipeline costs.

LIQUID FUELS

Little information is available regarding the level of investment that would be required to advance the liquid-fuels technology, as the technology is still very much in the research and development stage. The total amount required is likely to be significant.

ECBM

Little information is available about the level of investment that would be required to advance ECBM technology. Although the technology has operated at a pilot scale demonstration from 1995, there is little commercial activity in the industry as a result of a lack of adequate economic drivers (e.g. natural gas price is too low), along with mixed pilot results. The technology is still in the development phase and research is continuing. The total amount of investment required for commercial operation is likely to be significant.

4.4 ADDITIONAL CO_2 EMISSIONS FROM REUSE

In the act of re-using CO_2, the reuse technologies have a widely varying carbon footprint. This is largely related to the manufacturing process of the end product, irrespective of whether CO_2 is used in the process or not. The make-up power required for the capture plant provides a significant component of these emissions.

Edge Environment has undertaken a scoping life cycle analysis (LCA) for specific case studies for each of the CO_2 reuse technologies (refer Appendix M), with the following goal: To approximately assess the lifecycle CO_2-equivalent greenhouse gas emissions associated with the act of reusing CO_2 to produce some product or service, exclusive of any considerations of the permanence of storage in the product or service.

The results of this scoping LCA are shown below.

Table 4.3 LCA case study description and results

CO_2 REUSE APPLICATION	CASE STUDY	T CO_2-E EMITTED IN THE ACT OF REUSE OF 1 TONNE OF CO_2
Enhanced oil recovery	Capture from a coal-fired power station near the Dakota Gasification Plant in the USA. Delivered via pipeline to the Weyburn CO_2-EOR flood (e.g. surface processing and reinjection power comes from the Canadian Grid).	0.51
Bauxite residue carbonation	Capture from a coal-fired power station in Western Australia, supplying the Kwinana Alumina Refinery via a nine km pipeline.	0.53
Urea yield boosting	Capture from a coal-fired power station in China, supplying a urea plant via a nine km pipeline.	2.27
Enhanced geothermal systems	Capture from coal-fired power stations in SE QLD, Australia. Delivered via a 970km pipeline to the Cooper Basin, Australia.	0.58
Enhanced coal bed methane	Capture from a coal-fired power station in China (Yancheng), supplying a commercial ECBM operation in the South Quinshui Basin via a 50km pipeline.	0.44
Renewable methanol	Capture from the Svartsengi Geothermal Power Plant (Iceland). Process heat and power also supplied captive from this power station.	1.71
Formic acid production	Capture from a coal-fired power station in Korea, supplying CO_2 to the electrolysis plant via a nine km pipeline.	3.96
CO_2 concrete curing	Utilises a flue gas slipstream from a coal-fired power station in Nova Scotia, Canada, with the precast facility located in close proximity.	2.2 (see note 1)
Algae cultivation	Algae farm integrated with a coal-fired power station in Eastern Australia, with process requirements similar to those identified in public documents of MBD Energy.	0.42

CO_2 REUSE APPLICATION	CASE STUDY	T CO_2-E EMITTED IN THE ACT OF REUSE OF 1 TONNE OF CO_2
Carbonate mineralisation	PB estimate of requirements based on capture at a brown coal-fired power plant in Victoria, Australia, with no requirement for manufactured alkalinity.	0.32
Polymers	Capture from a coal-fired power station in the USA, delivered via a 9km pipeline to the polypropylene carbonate production facility.	5.52

Note 1: The use of anthropogenic CO_2 in concrete curing has genuine mitigation potential, with a good CO_2 balance expected when compared to a conventional concrete production method. In fact 90 per cent of the CO_2 emissions intensity listed above for CO_2 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.

There are three key points to note in relation to the results of the LCA.

- Firstly, a critical assumption of the analysis is that the CO_2 capture plant is a retrofit to the existing power generation fleet. Any parasitic losses due to the capture plant have to be replaced with extra power generation with emissions intensity comparable to the local grid. In several instances this 'make-up power' provides a significant component of the emissions attributed to CO_2 reuse.
- Secondly, the LCA considers emissions only up to the point of producing the defined product, be it oil recovered through EOR or biodiesel produced from algal oil. It does not include emissions that might result from use of these products, e.g. emissions from combustion of the oil, gas, biodiesel and release of CO_2 from urea in the field.
- Thirdly, results from the LCA show that emissions associated with reuse are very high for some technologies. However, this can in some cases be more a reflection on the industry that the CO_2 is being directed towards rather than a reflection on the emissions intensity of CO_2 reuse itself. For example, for CO_2 concrete curing 90 per cent of the emissions associated with reuse are actually attributable to cement manufacture, which would occur irrespective of whether CO_2 is used in the concrete curing process or not. To account for this issue, a benchmarking exercise would need to be undertaken to compare life cycle emissions from products produced via a CO_2 reuse pathway with products produced by 'conventional' pathways. This would be a logical extension of the LCA work undertaken to date.

4.5 REUSE TECHNOLOGIES APPLICABILITY TO DEVELOPING COUNTRIES

EOR, carbonate mineralisation, CO_2 concrete curing, bauxite residue treatment, ECBM, urea yield boosting and renewable methanol are likely to be of particular interest for developing countries such as China and India based on the potential market size and strength of demand for the end products.

The CCUS-TAP notes that 50 per cent of CCS projects deployed by 2020 should be in developing countries. It is also noted that the IEA suggest that 30 per cent of global CCS projects will need to be deployed in China and India by 2050 to provide the forecast required contribution to a global emissions reduction of 50 per cent. China and India are the natural focal points amongst the set of emerging and developing economies because of their very large size and continued rapid growth (in their economies and corresponding greenhouse gas emissions).

At present, very few projects are planned for developing countries, as typically there are no funding programs to support CCS deployment and there are other priorities for the spending of available public funds. Furthermore, developing nations argue that historically emissions have come from developed nations, and consequently it is the developed nations that should bear the cost of developing and deploying abatement technologies. Developed nations do not refute this argument, and a short-term goal of the CCUS-TAP is to support at least four industrial-scale CCS demonstrations of commercial scale in developing countries by 2015.

There is no globally accepted definition for a developing country. For operational and analytical purposes, the World Bank's main criterion for classifying economies is gross national income (GNI) per capita. The World Bank divides countries into low, lower-middle, upper-middle and high income groupings, with low and middle income countries commonly referred to together as developing economies. The International Monetary Fund (IMF) uses a flexible classification system that considers per capita income, export diversification, and extent of integration into the global financial system. The IMF's World Economic Outlook, April 2010, provides a convenient and up–to-date reference list of developing and emerging economies.

The relevance of each of the short-listed CO_2 reuse technologies to developing countries is discussed below. It is difficult to objectively identify a technology as being more applicable to developing countries than to developed countries. The CO_2 reuse technologies can provide a number of benefits common to both developing and developed countries, such as:

- a source of revenue;
- positive public relations and marketing, and possible international exposure for the company;
- use EOR to gain storage learning and develop public acceptance of storage;
- advancing capture technology development in locations where access to viable storage is not currently available;
- learning through the development of carbon capture components and CO_2 reuse technologies themselves;
- knowledge sharing opportunities;
- approvals process and stakeholder engagement process development;
- raising public awareness, perception and support of CCS and reuse technologies;
- environmental and social benefits; and
- jobs creation in the local community.

Since the benefits of the CO_2 reuse technologies and the potential advantages gained to accelerate CCS are generally equally applicable to both developing and developed countries, the main focus of the discussion below is based on the strength of demand for that particular product (derived from CO_2 reuse) in developing countries, particularly China and India. The demand for each of the short-listed reuse technologies and associated products in developing countries are described below.

4.5.1 MINERAL CARBONATION PRODUCTION AND CO_2 CONCRETE CURING

Mineral carbonation production and CO_2 concrete curing both have potential to provide net positive revenue as the processes utilise untreated flue gas and therefore does not require expensive capture and compression infrastructure. Furthermore, China and India together represent more than 55 per cent of world cement production, a good proxy for concrete production. The production capacity of both countries is also growing strongly. Consequently, these technologies have strong applicability to India and China, though neither technology is likely to accelerate the uptake of conventional capture plant since neither requires a purified/concentrated CO_2 stream.

At the 2009 China CCS Roundtable organised by the International Energy Agency (IEA), it was noted that the Chinese cement industry is only just learning about CCS, but would prefer to capture CO_2 for a revenue generating use rather than just for geological storage. The industry is interested to know more about global CO_2 capture developments in the cement sector.

4.5.2 BAUXITE RESIDUE CARBONATION

Developing countries account for 37 per cent of alumina production. China is the world's largest alumina producer (28 per cent of global production, with average production growth of 34 per cent between 2004 and 2008). Consequently, bauxite residue carbonation may have particular relevance to China. The technology requires a concentrated stream of CO_2, which provides an opportunity to introduce conventional capture plant. However, the total CO_2 required at any one alumina refinery site may be limited to <20MWe equivalent, so the size of project is likely to be limited by this factor.

4.5.3 ENHANCED COAL BED METHANE (ECBM)

Results from research into 29 possible ECBM sites in China have been used to estimate that CO_2 sequestration potential in the country's known coal beds could nominally be about 143Gt. This capacity could in principle sequester CO_2 emissions for an estimated 50 years based on China's CO_2 emission levels in 2000. In 2002, a joint Canadian-Chinese ECBM micro-pilot project was commenced, with the objective of characterising the sorption behaviour of the coal seams of the south Quinshui Basin. In November 2009 Phase II of the pilot project was initiated, with an extension of the operational area and commencement of dewatering operations. (Gunter). The CSIRO is also working on an ECBM pilot project in China.

Indonesia has large reserves with associated coal seam methane potential of approximately 8Gt methane, and therefore nominally also has significant CO_2-ECBM potential. This potential is thought to be greatest in southern Sumatra.

At the 2009 Brazil CCS Roundtable, Petrobas (the Brazilian National Oil and Gas Company) identified that they had one ECBM and one EOR project due to commence in the near future. The ECBM project, referred to as the Carbometano Brasil Project, will test CO_2-ECBM in deep unmineable coal seams in the Parana Basin.

Petrobas' primary interest in CCS is as a means of dealing with the CO_2 emissions that would otherwise result from the development of the 'Pre-salt' high CO_2 content oil fields. The power generation sector in Brazil is dominated by renewables (83 per cent), with a forecast increase in coal-fired capacity of only 6GW by 2030. Consequently, it appears that CCS in Brazil will be more relevant to the industrial sector than the power generation sector. Petrobas' developments provide evidence to support this line of thinking. Brazil's total ECBM potential is still being assessed.

4.5.4 UREA YIELD BOOSTING

The total global urea production in 2009 was 151.9Mtpa. China's urea production capacity is currently 65Mtpa, and growing strongly. However, it is understood that this capacity is comprised of many small to moderate size production facilities.

India ranks as the world's second largest urea producer, with an annual production of 21Mtpa. The International Fertilizer Association forecasts 17 per cent production growth in India between 2009 and 2013 to 25Mtpa production.

Natural gas is the dominant urea production feedstock internationally, including in India. However, in China 70 per cent of urea production utilises coal (gasified) as a feedstock, which results in surplus CO_2 such that additional CO_2 would not be required. With rising natural gas prices, the preference for coal as a feedstock is growing.

The dominance of coal as a urea feedstock in China results in reduced opportunities for other external CO_2 sources for boosting urea production. Coal gasification as a whole in China is a major source of high concentration CO_2 that is potentially available for reuse in other industries.

4.5.5 METHANOL

In 2007, China became the world's largest producer of methanol. Current world production of methanol is slightly above 40Mtpa (Methanol Producers Association). China's installed capacity is large, with actual production in 2010 expected to be approximately 17Mt.

For over a decade China has been developing research and demonstration programs for methanol and its derivative dimethyl ether as transport fuels. These efforts continue now. Chinese taxi and bus fleets are running on high methanol blends (M-85 to M–100), and retail pumps sell low level blends (M–15 or less) in many parts of the country.

Chinese demand for methanol in 2010 is anticipated to be approximately 21Mt.

Given China's current interest in methanol and dimethyl ether, renewable methanol technology using CO_2 as a feedstock is highly relevant.

4.5.6 FORMIC ACID

The global formic acid market is relatively small, currently less than 1Mtpa.

Production of formic acid is predominantly in Europe. BASF is the world's largest producer of formic acid, producing approximately 182,000tpa in Germany. Kemira Oyj produces in excess of 100,000tpa in Finland and is the world's second largest producer of formic acid. A production facility in the United Kingdom formerly owned by BP produces approximately 60,000tpa.

BASF also has a production facility in Nanjing, China, producing 50,000tpa. The Petrochemical Complex at Nanjing actually produces a wide range of chemicals with a total output of 1.7Mtpa. In line with its general industrial growth, Chinese domestic formic acid production is likely to increase in the future.

4.5.7 ENGINEERED GEOTHERMAL SYSTEMS

EGS may have significant relevance to developing countries such as China and India. Recent assessments of deep heat resources for EGS development have been performed for the United States (MIT, 2006), Germany, India and China. The assessments indicate significant potential, ≥100,000 MWe in the United States, with similar potentials estimated for parts of China and India. (This equates to a potential storage capacity of 876Mtpa based on a 5 per cent loss during CO_2 circulation, presuming CO_2 comes to be used as a heat exchange fluid).

However the use of supercritical CO_2 as the working fluid in EGS is currently in the early stages of research and development and there are a number of significant issues that need to be resolved. On this basis the timeframe to commercial deployment of the technology is likely to be more than 10 years away and therefore will not play a role in accelerating CCS deployment prior to 2020.

4.5.8 POLYMERS

The global market for polyethylene and polypropylene are approximately 80Mtpa and 45Mtpa respectively, representing the two largest polymer markets.

The global demand for low density polyethylene (LDPE) in 2009 was approximately 18.4 Mtpa and is expected to grow at a compound annual growth rate of around 2 per cent from 2009 to 2020. The Asian demand by volume for LDPE in 2009 was 5.9 Mt (consuming more than 30 per cent of the global market).

The polymer manufacturing technology utilising CO_2 as a feedstock may be of particular interest to developing countries such as India and China as they have both have considerable consumption potential of LDPE due to their large and growing populations. China is emerging as the major demand driver for LDPE in the world.

In terms of polycarbonate, the Asia Pacific region is the largest polycarbonate market worldwide, representing more than half of the global market. It has been estimated that China alone will account for 40 per cent of the global market in the next two to three years. Estimates from polycarbonate producers put growth rates in China up to 10 per cent per year.

4.5.9 ENHANCED OIL RECOVERY (EOR)

The top 10 oil producing countries, in decreasing order of production, are: Saudi Arabia, Russia, USA, Iran, China, Mexico, Canada, the United Arab Emirates, Venezuela, and Kuwait. According to the World Bank, only the United States and Canada are classified as advanced economies, with the remainder of the top ten oil producing nations classified as either developing or emerging economies.

CO_2-EOR is predominantly undertaken in North America (the United States and Canada are both amongst the top 10 oil producing nations), and has been for several decades. However, Saudi Arabia is showing interest in CO_2-EOR, with a project planned for 2013 injecting CO_2 into the Ghawar Field in the east of the country. (Morales, 2009). China also has significant EOR potential, with past pilot projects investigating CO_2-EOR in Chinese Oil Fields, and current developments including a joint project with Japan to capture 1-3Mtpa from the Harbin Thermal Power Plant in Heilungkiang Province, to be transported approximately 100kms to the Daqing Oilfield for EOR (Rødningsby, 2010).

In July 2010 Petrobras started the production of oil for the first time from the pre-salt layer of the Baleia Franca Field, off the coast of south eastern Espirito Santo state, Brazil. The pre-salt oil reserves have a high CO_2 content (close to 20 per cent), which will be re-injected for EOR. Indonesia's strong EOR potential is also widely recognised.

4.5.10 ALGAE CULTIVATION

Algae cultivation can result in varying types of end products, not only biofuels but also food, stock feed, renewable chemicals and many other products that are critical for a more sustainable society.

Developing countries are often situated in regions which are geographically interesting for algae cultivation -e.g. typically they have favourable climatic conditions and cheap labour. However, the biggest threat of algae cultivation in developing countries stems from the scale envisaged for mass production, in particular for algae based biofuels (ABB), which is in the order of magnitude of 1,000 ha. There are very few places on land suitable for algaculture at this scale. In summary solar irradiance and available marginal land are the main factors which will constrain the development of algae cultivation in developing countries.

* * * * *

The recurring message is that China is already a dominant CO_2 producer and consumer in most markets, with its market share only likely to further increase. As a result, the majority of the short-listed reuse technologies have applicability and potential for development in China.

Princeton University's Carbon Mitigation Initiative has reported on CCS opportunities in China, noting the following:

"China is unique in the large number (nearly 400) of existing and planned projects for making ammonia, methanol, and other fuels and chemicals from coal, natural by-products of which are nearly pure CO_2 streams. Some of the 20 CCS demonstration projects called for by the G8 might be expeditiously located in China – taking advantage of the relatively low cost of capturing these CO_2 streams (compared with capturing CO_2 from power plant flue gases). The researchers' analysis identified 18 coal-chemicals/fuels facilities, each emitting one million tonnes per year or more of CO_2 that are within 10 km of prospective deep saline aquifer CO_2 storage sites and an additional 8 facilities within 100 km." (Ninth Year Annual Report: CCS Early Action Opportunities in China, 2010).

4.5.11 CDM CREDITS

Debate has continued for many years on the issue of the eligibility of CCS projects for Clean Development Mechanism (CDM) Credits. At the Cancun climate change talks in December 2010, a draft decision was adopted by the Conference of Parties as follows: "Decides that carbon dioxide capture and storage in geological formations is eligible as project activities under the clean development mechanism…". The matter has been referred to the Subsidiary Body for Scientific and Technological Advice, which is responsible for developing the modalities and procedures for the inclusion of CCS as a CDM, with particular emphasis placed on the verifiability of the permanence of storage. Reuse technologies that sequester CO_2 in alternative forms, such as mineralisation, may be able to facilitate additional projects in developing countries through the CDM.

5. TECHNOLOGY EVALUATION

This section builds on the high level technology comparison completed in Section 4 and undertakes a more detailed evaluation of the short-listed reuse technologies. The technologies are evaluated against two key objectives; (1) accelerating cost reductions for CCS and (2) accelerating alternative forms of CCS.

5.1 METHODOLOGY AND SELECTION CRITERIA

The CO_2 reuse technologies are assessed using a set of selection criteria designed to align with the overall objectives for the project, e.g. to determine how and to what extent CO_2 reuse can advance the deployment of CCS and to potentially support projects which further the development of promising CO_2 reuse technologies. At a high level, this involves understanding the realistic forecast demand for CO_2 from different technologies and the commercial potential for captured CO_2 to meet this demand.

There are three main scenarios envisaged when implementing CO_2 reuse technologies:

- CO_2 reuse could provide additional revenues which offset some part of the costs of capture;
- CO_2 reuse could also provide long term storage of CO_2, and so act as a substitute for geological or other forms of storage (considered an alternative form of CCS); and
- CO_2 reuse could provide major additional revenues and so act as a deterrent to long term storage.

With these three scenarios in mind, the following criteria have been selected as the basis for classifying the CO_2 reuse technology, to assess the potential impact of the technology in accelerating the deployment of CCS:

- technology maturity.
- potential for scale-up.
- value for money.
- CO_2 abatement potential, environmental and social benefits.

These criteria are broken down into sub-criteria, described further in the following sections. A coarse quantitative scoring system was used for the assessment, involving an allocation of one, two or three points against each criterion. For two of the criteria a 'bonus point' approach was adopted wherein either a score of zero or one point was awarded.

A score of three indicates positive and reliable evidence that the technology displays preferred characteristic(s) for that criterion. Scores of two or one are corresponding less favourable, with one typically suggesting the technology shows little alignment with the preferred characteristics. The scoring system (three, two, and one) can be thought of in qualitative terms as representing strong, moderate and weak performance respectively for each of the preferred characteristics.

5.1.1 TECHNOLOGY MATURITY

As identified in section 4.1, the technologies considered are at different stages of development. Some are at a very early stage, some are approaching commercial operation (demonstration stage), and some are mature, established technologies.

In order for the selected technologies to have an impact in accelerating the uptake of CCS they should be promising technologies ready for commercialisation, as opposed to mature technologies or conceptual technologies some way short of commercialisation.

Whilst it is certainly true that the 'ready for commercialisation' technologies are most likely to see rapid growth in the next few years, often this growth is from a relatively small base. On the other hand, there is strong evidence to suggest that some mature technologies already applied on a large scale (for example EOR) still have potential for significant growth in the short term, and as such they warrant consideration as a potential market for captured CO_2. Therefore, the criterion does not penalise technologies that are already mature, if there is still growth potential.

This criterion by necessity assumes the technology becomes commercial at some point. The upper threshold of interest has been set to 'greater than 10 years' because a realistic carbon price scenario combined with cost reduction in carbon capture technology could result in CCS viability not long after 2020; hence reuse technologies only reaching viability after this point in time are of limited interest, as they do not provide acceleration of CCS. As is outlined in Part 2 – Section 4, the most significant cost reductions in CCS technologies will most likely be realised during the first few gigawatts (GW) of deployment, which is expected to occur in the next ten years.

This criterion has not been broken down into sub-criteria.

CRITERIA 1.01: TIMEFRAME TO DEPLOYMENT	
3	≤5 years, including newly commercialised and mature technology
2	5–10 years
1	>10 years

5.1.2 SCALE-UP POTENTIAL

This criterion is composed of two sub-criteria: (1) total demand and (2) geographical constraints on the production system.

5.1.2.1 Total demand

This criterion estimates the total realistic level of demand which could be expected to arise from this technology if it reached its maximum potential. To significantly advance CCS, reuse technologies will need to demand large quantities of CO_2.

Preference is given to technologies for CO_2 reuse which have potential to provide larger volumes of CO_2 reuse over time.

This assessment is based on analysis of the possible impacts of CO_2 use on the scale and rate of growth of the markets for their products, and the financial position of the manufacturing and other processes.

CRITERIA 2.01: TOTAL DEMAND	
3	>300Mtpa CO_2 equivalent (>1 per cent of global fossil fuel emissions)
2	>30Mtpa CO_2 equivalent (>0.1 per cent of global fossil fuel emissions)
1	<30Mtpa CO_2 equivalent (<0.1 per cent of global fossil fuel emissions)

5.1.2.2 Geographical constraints on the production system

This criterion is designed to complement criterion 2.01, by taking into consideration geographical constraints that may prevent the technology from reaching its full scale potential, or limit its application to a few advantageous locations across the globe.

CRITERIA 2.02: GEOGRAPHICAL CONSTRAINTS ON THE PRODUCTION SYSTEM	
3	Technology applicable at most locations, products transportable at low cost
2	The maximum scale of the technology is restricted by land or other resource constraints or only applicable at selected locations or transport of products is relatively expensive.
1	Major limitations on maximum scale, suitable locations, and ease of transportation of products.

5.1.3 VALUE FOR MONEY

This criterion is composed of three sub-criteria, commercial viability, competitiveness with other technologies and barriers/drivers/incentives.

5.1.3.1 Commercial viability

This criterion considers the costs and the potential revenues of using CO_2 in the technology. If there are alternatives to CO_2 in the technology, the relative costs of using CO_2 and the alternatives are considered.

CRITERIA 3.01: COMMERCIAL VIABILITY	
3	Predicted to be commercially viable with current market conditions, and without a carbon price or equivalent incentive
2	Requires either increased market prices for competitor products, or a carbon price, or both, in order to be commercially viable
1	Never likely to be viable

5.1.3.2 Competitiveness with other technologies

In order for a CO_2 reuse technology to advance CCS, the use of the CO_2 would have to be price-competitive with alternative technology achieving the same outcome. For example, for significant uptake of CO_2-ECBM to occur it would need to have favourable economics compared to N_2-ECBM or flue gas ECBM. As another example, CO_2 derived liquid fuels may see reduced demand and price in the future as electric vehicle technology matures.

CRITERIA 3.02: COMPETITIVENESS WITH OTHER TECHNOLOGIES	
3	Few or no significant competitor technologies have been identified
2	Non CO_2 based alternative technology pathways/solutions exist that will compete for market share
1	Significantly cheaper alternative technology pathways/solutions exist

5.1.3.3 Barriers / incentives / drivers

This criterion considers any financial incentives, such as funding from public bodies, which might support the technology, as well as any other barriers or drivers.

CRITERIA 3.03: BARRIERS / INCENTIVES / DRIVERS	
3	National incentives or legislation exist that will support the technology; no major barriers.
2	Limited specific support in the form of national incentives or legislation; no major barriers identified.
1	Major barriers identified.

5.1.4 CO_2 ABATEMENT POTENTIAL, ENVIRONMENTAL AND SOCIAL BENEFITS

This criterion is composed of four sub criteria; permanence of storage, additional CO_2 emissions from reuse, environmental benefit and social benefit, two of which are "bonus" criteria. These are all described in more detail below.

5.1.4.1 Permanence of storage

CO_2 reuse that has an alternative form of storage has significant potential to accelerate the uptake of CCS, albeit in an alternative embodiment. For this reason and also because any form of storage is preferred from an environmental viewpoint, CO_2 reuse with associated higher degrees of storage are preferable.

CRITERIA 4.01: PERMANENCE OF STORAGE	
3	Permanent
2	Mixture of permanent and non permanent
1	Non-permanent

5.1.4.2 Additional CO_2 emissions from reuse

Based on the scoping level life cycle assessment (LCA) conducted by Edge Environment (Appendix M), this criterion is intended to quantify the CO_2 emissions associated with reuse of the CO_2, particularly CO_2 emissions due to the energy input into the reuse process. In combination with 4.01 (which penalises when the CO_2 is not sequestered), this gives an indication of the lifecycle CO_2 performance. It should be noted that this criteria does not take into consideration emissions associated with use of the end product, for example the emissions associated with the utilisation of crude oil extracted by EOR, owing to the wide and varied possible uses of some end products.

From an environmental perspective, reuse technologies that result in significant additional CO_2 emissions through the act of reuse are considered less desirable, particularly those that release more CO_2 in the act of reuse than if the CO_2 had simply been emitted in the first place.

CRITERIA 4.02: ADDITIONAL CO_2 EMISSIONS FROM REUSE	
3	Emissions of CO_2 per tonne of CO_2 reused < 0.5t/t
2	Emissions of CO_2 per tonne of CO_2 reused > 0.5t/ t but <1t/t
1	Emissions of CO_2 per tonne of CO_2 reused > 1t/t

5.1.4.3 Environmental benefit (4.03) and social benefit (4.04)

These two criteria are in the form of bonus points.

Technologies that display recognisable environmental or social benefits may derive some advantage from these benefits in the form of a greater likelihood of receiving public and government support.

It is important to note that these criteria only consider those environmental and social benefits which are not directly related to the CO_2 abatement potential of a particular reuse technology.

CRITERIA 4.03: ENVIRONMENTAL BENEFIT (NON CO_2 ABATEMENT RELATED)	
Bonus point – 1 or 0	Example of bonus point: Bauxite Residue Carbonation neutralises a strongly alkaline waste, and the resulting product has the potential to be used as a soil amendment on acidic soils – this has been trialled in Western Australia. This would receive the bonus point.

CRITERIA 4.04: SOCIAL BENEFIT (NON CO_2 ABATEMENT RELATED)	
Bonus point – 1 or 0	Example of bonus point: If a particular application has the potential to improve public acceptance, or has higher employment intensity compared to fossil fuel alternatives, it would receive the bonus point.

5.2 LIMITATIONS OF ANALYSIS

5.2.1 SHORTAGE OF INFORMATION

The investigation to date has taken the form of a desktop based research study, with limited or no contact with industry proponents. Subsequently, a significant hurdle in the analysis was the lack of availability of good quality, reliable information. This was more evident on some technologies than others – those technologies which were less developed or being developed on a smaller scale had less relevant information in the public domain.

5.2.2 COMPARABILITY OF INFORMATION

Due to a number of factors such as lack of information, stage of technology development and speciality of technology, it was difficult to perform a like for like comparison of the technologies at a detailed level.

Therefore, based on the above factors, the technologies were assessed on an individual basis and scored separately and distinctly rather than relatively. In cases where there was insufficient information available the score was marked down to reflect this uncertainty.

5.3 EVALUATION OF SHORT-LISTED TECHNOLOGIES

The following section provides a completed evaluation summary table for each of the short-listed CO_2 reuse technologies. The evaluation summary presents the supporting information which formed the basis for scoring as per the criteria outlined in Section 5.1.

Full results of the evaluation scoring process for each technology are provided in Appendix K. The scores are summarised in Table 5.11 with analysis and discussion of the results provided in Section 6.

5.3.1 CO_2 FOR USE IN ENHANCED OIL RECOVERY

Table 5.1 EOR evaluation summary

EOR EVALUATION SUMMARY	
Timeframe to commercial deployment	Commercialised technology.
Scale-up potential	EOR is currently widely employed in the US, but there is significant potential for global growth.
Geographical constraints on the production system	Maximum deployment of the technology is constrained by location of depleted oil and gas fields, and transport of CO_2.
Commercial viability	Technology is commercially viable.
Competitiveness with other technologies	EOR technology can be implemented using CO_2, water or nitrogen as the transmission fluid. CO_2 reuse EOR will have to prove competitive with these alternatives .
Barriers / incentives / drivers	Barriers are unclear regulations and uncertain public support (particularly for onshore injection). Driver for deployment is expected demand growth for crude oil .
Permanence of storage	During CO_2-EOR applications, more than 50 per cent and up to 67 per cent of injected CO_2 will return to the surface with the extracted oil, requiring separation and reinjection into the reservoir. At the end of CO_2-EOR operations, CO_2 should remain permanently sequestered in the depleted oil reservoir. Appropriate measurement, monitoring and verification systems must be in place to verify the permanence of the sequestration. It remains to be seen how the emissions associated with the combustion of the additional oil recovered will be viewed under any emissions trading scheme. Where natural CO_2 reserves would otherwise be used for EOR, use of anthropogenic CO_2 represents a real net decrease in emissions of CO_2.
CO_2 emissions in the process of reuse	Edge Environment Case Study Result: 0.51t CO_2-e/t reused. Case Study Description: Capture from a coal-fired power station near the Dakota Gasification Plant in the USA, delivered via pipeline to the Weyburn CO_2-EOR flood (e.g. surface processing and reinjection power comes from the Canadian Grid).
Environmental benefits (non CO_2 abatement related)	No specific environmental benefits have been identified.
Social benefits (non CO_2 abatement related)	EOR-based demonstration projects coupled with MMV provide a platform for community acceptance of geological storage as well as valuable storage science and technology learning.

5.3.2 CO_2 AS FEEDSTOCK FOR UREA YIELD BOOSTING

Table 5.2 Urea yield boosting evaluation summary

UREA YIELD BOOSTING EVALUATION SUMMARY	
Timeframe to commercial deployment	Urea has been produced on an industrial scale for over 40 years. The technology is well understood and can be considered mature. CO_2 capture from reformer flue gas at urea plants is relatively new, first introduced in the late 1990's. MHI have several units operational in the 100-400tpd CO_2 range.
Scale-up potential	Urea production is carried out on a very large industrial scale. The size of plant is constrained only by the size of the upstream ammonia facility. A typical plant may produce 1,500 tonnes of urea per day, systems up to 5,000 tonnes per day are considered feasible. However, surplus ammonia from natural-gas based plants may be in the range 5 per cent–10 per cent. Consequently, capture plants installed for this purpose will continue to be <1000tpd in size.
Geographical constraints on the production system	Ammonia and urea plants are typically located on the same site and close to major sources of natural gas. Reformer flue gas is the usual choice for CO_2 capture, so there is no major geographical constraint on urea yield boosting in that sense. However, CO_2 may be captured more cheaply from alternative sources, and delivered via pipeline to the urea plant – this approach is clearly reliant on suitable CO_2 sources in proximity to the urea plant.
Commercial viability	The production of urea is an established technology with a proven commercial viability, albeit with use of captive CO_2. If urea demand (and price) is strong relative to ammonia, then there will be incentive to convert the small per centage of surplus ammonia to urea buying available concentrated CO_2 or by installing additional CO_2 capture plant.
Competitiveness with other technologies	Nitrogen fertiliser is a product with an established global market with current urea prices at US$225-US$290 per tonne. To enter the market the urea produced using recycled CO_2 needs to be at or below the current market prices, after processing and transport costs.
Barriers / incentives / drivers	The volatility in the price and demand of urea and ammonia makes long term appraisal of the capital investment in CO_2 capture plant difficult.
Permanence of storage	Not permanent – CO_2 is stored temporarily before the reaction used to form urea is reversed when the fertiliser is applied to the land.
CO_2 emissions in the process of reuse	Edge Environment Case Study Result: 2.27t CO_2-e/t reused. Case Study Description: Capture from a coal-fired power station in China, supplying a Urea Synthesis plant via a 9km pipeline.
Environmental benefits (non CO_2 abatement related)	No additional environmental benefits have been identified.
Social benefits (non CO_2 abatement related)	No additional social benefits have been identified.

5.3.3 CO_2 AS A WORKING FLUID FOR ENHANCED GEOTHERMAL SYSTEMS

Table 5.3 Enhanced geothermal systems evaluation summary

ENHANCED GEOTHERMAL SYSTEMS EVALUATION SUMMARY	
Timeframe to commercial deployment	>10 years
Scale-up potential	A very large theoretical market potential exists, greater than 30Mtpa CO_2, based on conservative estimate of approximately 70 EGS sites of 500MWe capacity.
Geographical constraints on the production system	Similar constraints as can be expected for CCS; a major point source emitter is required in the region of the geothermal formation. Increased distances will have significant cost implications for compression and pipeline.
Commercial viability	Enhanced geothermal systems are unlikely to be commercially viable without a carbon price, and significant investment in the short to medium term.
Competitiveness with other technologies	CO_2 as a working fluid will have to prove competitive against using water as a working fluid. Similarly geothermal power will need to prove competitive with current energy sources. Displacement of alternatives is unlikely in the short to medium term.
Barriers / incentives / drivers	Renewable energy market is expected to see dramatic growth in the next 10 years, with many countries creating incentives for new technologies through renewable energy targets and credit systems. Suitability of geothermal reservoirs as permanent CO_2 storage reservoirs is uncertain.
Permanence of storage	The process has the potential to sequester permanently, but this is dependent on a suitable capping formation above the geothermal resource.
CO_2 emissions in the process of reuse	Edge Environment Case Study Result: 0.58t CO_2-e/t reused. Case Study Description: Capture from coal-fired power stations in SE QLD, Australia, delivered via a 970km pipeline to the Cooper Basin, Australia.
Environmental benefits (non CO_2 abatement related)	No specific additional environmental benefits identified.
Social benefits (non CO_2 abatement related)	No specific additional environmental benefits identified.

5.3.4 CO_2 AS FEEDSTOCK FOR POLYMER PROCESSING

Table 5.4 Polymer processing evaluation summary

POLYMER PROCESSING EVALUATION SUMMARY	
Timeframe to commercial deployment	5–10 years
Scale-up potential	Assuming a conservative 4 per cent annual growth on existing PE / PP markets over the next five years, and assuming a displacement of 40 per cent of the PE and PP market would see over 30Mtpa CO_2 used as feedstock. The price fluctuations of finite petroleum feedstock could also lead to increased use of CO_2 feedstock polycarbonates and scale-up potential.
Geographical constraints on the production system	Technology is applicable at most varied locations.
Commercial viability	Commercial viability of the technology will depend on the products being accepted by the existing market. Some uncertainty due to lack of reliable information and demonstration projects.
Competitiveness with other technologies	Novomer claims products can be used as an alternative to existing petroleum based polymers, though this is still to be verified.
Barriers / incentives / drivers	Difficulties of entering existing product market. However, volatility of petroleum prices may drive deployment of technology.
Permanence of storage	Depends on end use – in pure form CO_2 polymers can degrade and break-down (re-releasing CO_2), in as short as 6 months in the right conditions. On the other hand the produced polymer may be embedded in a long-life product.
CO_2 emissions in the process of reuse	Edge Environment Case Study Result: 5.5t CO_2-e/t reused. Case Study Description: Capture from a coal-fired power station in the USA, delivered via a 9km pipeline to the polypropylene carbonate production facility.
Environmental benefits (non CO_2 abatement related)	No additional environmental benefits identified.
Social benefits (non CO_2 abatement related)	Carbon capture in items such as plastic bags and food packaging, which are used regularly, could make the issue of carbon abatement more relevant and practical to help public acceptance.

5.3.5 CO_2 FOR USE IN ALGAE CULTIVATION

Table 5.5 Algae cultivation evaluation summary

ALGAE CULTIVATION EVALUATION SUMMARY	
Timeframe to commercial deployment	5–10 years
Scale-up potential	Commercial scale systems would be in the region of 10–100Ha. And may be expected to absorb anywhere between 500 and 55,000tpa CO_2 per system.
Geographical constraints on the production system	The amount of CO_2 which can be captured from a point source will be constrained by the land available on a case by case basis. Systems are ideally suited to locations with high solar irradiance and adequate marginal land. Access to a water source is also important. Products can be readily transported using existing methods and infrastructure.
Commercial viability	The likely use of the algae would be for the large scale production of bio-fuel which has a large potential market. It is forecast that by 2022 algae bio-fuels will be the largest bio-fuel category overall, accounting for 40 billion of the estimated 109 billion gallons of bio-fuels produced (Bradford 2009). The high land requirement may limit the commercial viability of the technology in areas with high land prices.
Competitiveness with other technologies	On a wider scale algae bio-fuel will have to compete with current fuel sources (e.g. petroleum) if it is to be considered as a commercial alternative for use as a transport fuel. At present it appears unlikely that algae bio-fuel will be able to compete with alternative products in the current market.
Barriers / incentives / drivers	The technology is most suited to regions with high solar resource and large areas of marginal land surrounding point CO_2 sources (providing the most productive environment for algae cultivation) which will inhibit the implementation of the technology in many regions. The use of algal bio-fuels avoids the current food vs. fuel problems surrounding first generation soy/palm/corn/wheat/canola bio-fuels.
Permanence of storage	CO_2 which is absorbed by algae is used to generate biomass. Dependent on the system there may be a mixture of end products produced from this. A basic system may generate only biodiesel in this case the storage is temporary as the CO_2 is re-released when the fuel is burnt. Another system may generate biodiesel, supply crude algal oil for processing to plastics, useful nutraceuticals may be extracted and used in food supplements, the algal biomass remaining after extraction may then go on to produce animal feed, fertiliser, biochar or to be digested anaerobically to produce biogas. Some of these avenues will result in semi-permanent storage, and those that displace fossil fuels also have an indirect mitigation effect.
CO_2 emissions in the process of reuse	Edge Environment Case Study Result: 0.41t CO_2-e/t reused Case Study Description: Algae farm integrated with a coal-fired power station in Eastern Australia, with process requirements similar to those identified in public documents of MBD Energy

ALGAE CULTIVATION EVALUATION SUMMARY	
Environmental benefits (non CO_2 abatement related)	Algae cultivation systems can be used as a step in waste water treatment – to remove certain compounds from waste water/sewage. When char is produced from the algal biomass, it may be used as a soil conditioner. Algal meal when used as a livestock feed may reduce methane emissions.
Social benefits (non CO_2 abatement related)	Algae systems which are constructed on marginal land and used to produce bio-fuels would not compete with food crops for arable land. The use of algal bio-fuels avoids the current food vs. fuel problems surrounding first generation soy/palm/corn/wheat/canola bio-fuels.

5.3.6 CO_2 AS FEEDSTOCK FOR CARBONATE MINERALISATION

Table 5.6 Carbonate mineralisation evaluation summary

CARBONATE MINERALISATION EVALUATION SUMMARY	
Timeframe to commercial deployment	≤5 years
Scale-up potential	Market potential greater than 300Mtpa CO_2 equivalent, considering global aggregate consumption in excess of 30 billion tonnes per annum.
Geographical constraints on the production system	The maximum scale of the technology is restricted by the available resources of brine and fly ash to provide the requisite hardness and alkalinity required. If the brine source is not suitable or an abundant in supply then the technology requires manufactured alkalinity.
Commercial viability	Likely to be commercially viable without the need for a carbon price or similar incentive.
Competitiveness with other technologies	Initial market entry may be hampered by potential public perception of the products being inferior to existing alternatives and for the method to be accepted and approved by regulators.
Barriers / incentives / drivers	Plant capital cost still relatively high.
Permanence of storage	Permanent
CO_2 emissions in the process of reuse	Edge Environment Case Study Result: 0.32t CO_2-e/t reused Case Study Description: PB Estimate of requirements based on capture at a brown-coal fired power plant in Victoria, Australia, with no requirement for manufactured alkalinity. Actual result could be significantly higher, depending on the source of alkalinity, transportation distance, and end use.
Environmental benefits (non CO_2 abatement related)	The technology has the capability to reuse fly ash in the process which in the future may be considered and designated as a hazardous material requiring regulated storage.
Social benefits (non CO_2 abatement related)	One of the by products is fresh water that could be used as potable water, irrigation water, or an industrial water supply, which may alleviate the water deficit in some regions.

5.3.7 CO_2 FOR USE IN CONCRETE CURING

Table 5.7 Concrete curing evaluation summary

CONCRETE CURING EVALUATION SUMMARY	
Timeframe to commercial deployment	Based on plans for a demonstration plant in 2011, commercialisation could be achieved as early as 2012.
Scale-up potential	Based on 5 billion tonnes of concrete used globally per annum, and an estimated 10 per cent is pre-cast concrete, there is potential for 60Mtpa of CO_2 to be sequestered by concrete curing.
Geographical constraints on the production system	The reuse of CO_2 for concrete curing can only occur at precast concrete plants. Generally onsite flue gas emissions will be used, and/or from local/ neighbouring combustion sources.
Commercial viability	The technology has potential for commercial viability, assuming it becomes proven. Concrete curing, via a moist, controlled environment, is an established practice required to strengthen and harden precast concrete.
Competitiveness with other technologies	Concrete cured using this technology is unlikely to be able to be sold at a premium over existing products and therefore its competitiveness will be determined by the costs that can be saved (through reduced curing times, carbon tax etc.) in using this technology over traditional methods.
Barriers / incentives / drivers	The main barriers to concrete curing is the limitation of its use to existing concrete producers due to the requirement for it to be implemented at the precast concrete plants. The main drivers and incentives for the commercialisation of the technology are the potential to reduce curing times of concrete and the ability to capitalise on any applicable carbon schemes.
Permanence of storage	The mineral carbonation and curing process presents permanent storage of CO_2 for centuries in the form of precast concrete products.
CO_2 emissions in the process of reuse	Edge Environment Case Study Result: 2.20t CO_2-e/t reused Case Study Description: Utilises a flue gas slipstream from a coal-fired power station in Nova Scotia, Canada, with the precast facility located in close proximity.
Environmental benefits (non CO_2 abatement related)	There are no hazardous chemicals needed or produced by this process, the only by-products are water and heat.
Social benefits (non CO_2 abatement related)	No specific social benefits have been identified.

5.3.8 CO_2 FOR USE IN BAUXITE RESIDUE CARBONATION

Table 5.8 Bauxite residue carbonation evaluation summary

BAUXITE RESIDUE CARBONATION EVALUATION SUMMARY	
Timeframe to commercial deployment	≤5 years.
Scale-up potential	Limited. Technology only utilises approximately 30kg CO_2 per tonne of dry residue.
Geographical constraints on the production system	Requires local, high concentration source of CO_2 in proximity to aluminium refinery.
Commercial viability	Has been proven to be commercially viable at current scale by Alcoa (2.5Mpta residue treated using 70,000tpa CO_2), however this particular project is only viable because of the presence of a stream of concentrated CO_2 from a local ammonia plant.
Competitiveness with other technologies	Resulting product has limited use, and is not expected to have a commercial value.
Barriers / incentives / drivers	A high concentration (and potentially high pressure) of CO_2 is required. To be commercially viable, a local source of CO_2 is required.
Permanence of storage	CO_2 which is converted to carbonates is permanently sequestered. Further utilisation of CO_2 is possible by conversion to bi-carbonates, however over the long term, the CO_2 would be released from bi-carbonates in the conversion back to carbonates.
CO_2 emissions in the process of reuse	Edge Environment Case Study Result: 0.53t CO_2-e/t reused. Case Study Description: Capture from a coal-fired power station in Western Australia, supplying the Kwinana Alumina Refinery via a 9km pipeline.
Environmental benefits (non CO_2 abatement related)	Reduces dusting potential of red mud (currently an environmental hazard) and reduces the area of land and cost required for red mud disposal.
Social benefits (non CO_2 abatement related)	No specific social benefits identified.

5.3.9 CO_2 AS A FEEDSTOCK FOR LIQUID FUEL PRODUCTION

Table 5.9 Liquid fuel production evaluation summary

LIQUID FUEL PRODUCTION EVALUATION SUMMARY (RENEWABLE METHANOL; FORMIC ACID AS A HYDROGEN ENERGY CARRIER)	
Timeframe to commercial deployment	1. ≤5 years: CRI is currently constructing a five million litre per annum commercial demonstration plant in Iceland. Methanol will be blended with conventional unleaded petrol and sold at Olis gasoline stations throughout the greater Reykjavik area. 2. >10 years: Mantra claims to be close to commencing an ERC demonstration project (the CO_2 to formic acid part of the chain) of unspecified capacity in South Korea. However, there is no evidence of proponents developing the formic acid to hydrogen part of the chain.
Scale-up potential	Displacement of 10 per cent of the world's fossil petroleum consumption with renewable CO_2 derived fuels would represent in excess of 1Gtpa CO_2 recycling.
Geographical constraints on the production system	1. CRI's preferred plant embodiment/configuration co-locates with a geothermal power station and utilises the power station as the source of electricity and CO_2. Electricity grids with a lower CO_2 emissions intensity or a captive/dedicated renewable/zero emissions electricity supply for the project are realistically required to achieve any net decrease in CO_2 emissions as compared to fossil fuel alternatives. 2. No comment.
Commercial viability	1. Statements by CRI suggest the technology will be viable now in locations where the fuel price: electricity price ratio is large (e.g. Iceland). 2. Not likely to be viable in its current embodiment. On an energy equivalent basis, US$2/L gasoline equates to US$320/t formic acid, or US$338/t CO_2 input. To break even on the cost of energy input alone would require an electricity price of no greater than US$42/MWh (unlikely for a renewable energy input).
Competitiveness with other technologies	1. Electric vehicles are emerging as a viable alternative to liquid-fuelled vehicles. At present, they already have lower running costs than petroleum fuelled equivalent vehicles thanks to the relatively low cost of off-peak grid electricity and the benefits of regenerative braking. 2. Not likely to be competitive considering it is not likely to be commercially viable.
Barriers / incentives / drivers	1. Private funding only – no government support. 2. The National Research Council of Canada Industrial Research Assistance Program (NRC-IRAP) has agreed to fund 50 per cent of the costs associated with the development of Mantra's ERC technology.
Permanence of storage	Non-permanent. For mobile transportation, it is reasonable to assume that CO_2 released from the combustion of the liquid fuels derived from CO_2 cannot practically be captured for further processing or reuse.

LIQUID FUEL PRODUCTION EVALUATION SUMMARY (RENEWABLE METHANOL; FORMIC ACID AS A HYDROGEN ENERGY CARRIER)	
CO_2 emissions in the process of reuse	The CO_2 balance depends largely on the source of electricity. A dedicated renewable source of electricity has small emissions intensity, and consequently the additional emissions of CO_2 would be less than 0.5t CO_2 per tonne CO_2 reused. However, if grid power is used, the majority of countries have sufficiently high emissions intensity that the CO_2 balance is not so attractive. Renewable Methanol Case Study Result: 1.71t CO_2-e/t reused; Case Study Description: Capture from the Svartsengi Geothermal Power Plant (Iceland), process heat and power also supplied captively from this power station. Formic Acid Case Study Result: 3.96t CO_2-e/t reused; Case Study Description: Capture from a coal-fired power station in Korea, supplying CO_2 to the electrolysis plant via a 9km pipeline
Environmental benefits (non CO_2 abatement related)	No additional specific environmental benefits have been identified.
Social benefits (non CO_2 abatement related)	No specific social benefits have been identified.

5.3.10 CO_2 IN ENHANCED COAL BED METHANE RECOVERY

Table 5.10 Enhanced coal bed methane evaluation summary

ENHANCED COAL BED METHANE EVALUATION SUMMARY	
Timeframe to commercial deployment	Timeframe to commercial deployment is considered a minimum of 5 years away given the technical constraints to be overcome.
Scale-up potential	Coal seams are the most abundant fossil fuel deposits (in comparison to oil and gas reservoirs) so there is nominally potential for ECBM to become widespread on un-mineable coal seams if the technology barriers can be overcome. Results from research in 29 possible ECBM sites in China have been used to estimate that nominal CO_2 storage potential is about 143Gt in the country's known coal beds.
Geographical constraints on the production system	Maximum deployment of the technology is constrained by location of coal beds, and transport of CO_2 and natural gas.
Commercial viability	Technology may be commercially viable if further research succeeds in overcoming technical barriers, and as market conditions (natural gas price, carbon price) change.
Competitiveness with other technologies	The ECBM process may alternatively use N_2. The Alberta study has shown that flue gas (which comprises mainly of nitrogen and carbon dioxide) injection has its merits. Therefore, when economic and CO_2 storage factors are considered, there might be an ideal CO_2/N_2 composition where both factors will be optimised.

ENHANCED COAL BED METHANE EVALUATION SUMMARY	
Barriers / incentives / drivers	The primary barriers are the technical and related cost constraints on injectivity, and the potential sterilisation of coal resources that could be mined in the future using deep conventional mining methods or underground coal gasification. The driver for deployment is expected demand growth for energy in natural gas, potentially incentives provided by western governments offering a carbon price.
Permanence of storage	Storage of CO_2 once injected in a coal seam is essentially permanent, as it is adsorbed to the coal. A key assumption is that coal seam remains undisturbed, and is not subsequently mined or gasified in-situ in the future.
CO_2 emissions in the process of reuse	Edge Environment Case Study Result: 0.44t CO_2-e/t reused Case Study Description: Capture from a coal-fired power station in China (Yancheng), supplying a commercial ECBM operation in the South Quinshui Basin via a 50km pipeline.
Environmental benefits (non CO_2 abatement related)	No specific environmental benefits have been identified.
Social benefits (non CO_2 abatement related)	No specific social benefits have been identified.

5.4 SUMMARY OF EVALUATION SCORES

The completed evaluation for each of the short-listed technologies can be found in Appendix K. The scores are summarised in Table 5.11 below.

Table 5.11 Evaluation scores

	VARIOUS						MINERALISATION			LIQUID FUELS	
CRITERION	EOR	ECBM	UREA	EGS	POLYMERS	ALGAE	CARBONATE AGGERGATE	CONCRETE CURING	RED MUD CARBONATION	RENEWABLE METHANOL	FORMIC ACID
1.01 Timeframe to deployment	3	2	3	1	2	2	3	3	3	2	1
2.01 Scale-up potential	3	3	1	2	2	2	3	2	1	2	3
2.02 Geographical constraints on the production system	2	2	3	1	3	2	2	1	2	2	2
3.01 Commercial viability	3	2	2	2	2	2	3	2	2	2	1
3.02 Competitiveness with other emerging technologies	3	3	2	1	2	1	2	2	2	2	1
3.03 Barriers/ incentives/ drivers	2	2	2	1	2	1	2	2	1	2	2
4.01 Permanence of Storage	2	3	1	2	1	3	3	1	2	1	1
4.02 Additional CO_2 emissions from reuse	0	0	0	0	0	1	1	0	1	0	0
4.03 Environmental benefit (Non CO_2 abatement related)	0	0	0	0	0	1	1	0	1	0	0
4.04 Social benefit	0	0	0	0	1	1	1	0	0	0	0
1. Technology maturity	100%	67%	100%	33%	67%	67%	100%	100%	100%	67%	67%
2. Scale-up potential	83%	83%	67%	50%	83%	67%	83%	50%	50%	67%	83%
3. Commercial viability	89%	78%	67%	44%	67%	44%	78%	67%	56%	67%	44%
4. CO_2 abatement potential, environmental and social	50%	63%	38%	63%	63%	75%	88%	75%	75%	38%	38%
Total (no weighting)	77%	77%	58%	50%	65%	65%	88%	62%	62%	54%	46%

6. ANALYSIS AND DISCUSSION

A semi-quantitative ranking process identified the following five technologies as having the greatest potential to accelerate cost reductions for conventional capture plant: (1) EOR, (2) Bauxite residue carbonation, (3) Urea production, (4) Polymer production and (5) ECBM. Further analysis identified EOR and ECBM as the two technologies best placed to accelerate cost reductions for large capture plant, e.g. >100MW equivalent capacity.

A semi-quantitative ranking process identified the following five technologies as having the greatest potential to accelerate alternative forms of CCS: (1) carbonate mineralisation, (2) EOR, (3) algae cultivation, (4) concrete curing (5) ECBM.

The following section analyses and discusses the performance of the short-listed CO_2 reuse technologies against two key objectives; (1) accelerating cost reductions for CCS and (2) accelerating alternative forms of CCS.

6.1 PERFORMANCE OF TECHNOLOGIES AGAINST OBJECTIVES

The following analysis considers two possible objectives that may motivate investment into CO_2 reuse technologies, and assesses how well the short-listed technologies may meet these objectives.

a. Accelerate cost reductions for conventional CO_2 capture plant by generating revenue to offset the costs of capture where storage is not possible and/or where no carbon price exists

b. Accelerate the uptake of alternative forms of CCS e.g. not conventional capture plants with geological storage, but any technology or process that utilises a concentrated stream of CO_2 or a flue gas stream and sequesters the CO_2 permanently in any form, e.g. mineralisation.

To facilitate this comparison, different weightings were applied to the criteria to put an emphasis on those which are most relevant to meeting the particular objective. This resulted in an indicative measure of the performance of the short-listed technologies against each objective, allowing the technologies to be ranked accordingly.

6.1.1 OBJECTIVE A: ACCELERATE COST REDUCTIONS FOR CONVENTIONAL CO_2 CAPTURE PLANT

EOR is the reuse technology that is most likely to meet the objective of accelerating cost reductions for conventional capture plant on a scale commensurate with existing stationary power generation.

To measure the capability of the short-listed technologies to accelerate cost reductions for conventional capture plant, there are two main issues to be considered:

a. The technology must require a concentrated stream of CO_2, as would be produced by a capture plant at a power station. As a result, this requirement rules out algae cultivation, mineral carbonation and concrete curing technologies as these three applications can generally utilise untreated flue gas directly. These technologies, which do not require a concentrated stream of CO_2, are excluded from the assessment under this objective.

b. The technology must already be deployed commercially, or deployment must be imminent since the major cost reductions in capture plant are likely to occur within the first few gigawatts of deployment. A target of 20 commercial demonstration projects operational before 2020 might amount to the order of 6GW, meaning that the majority of capture plant cost reductions could happen within the next decade.

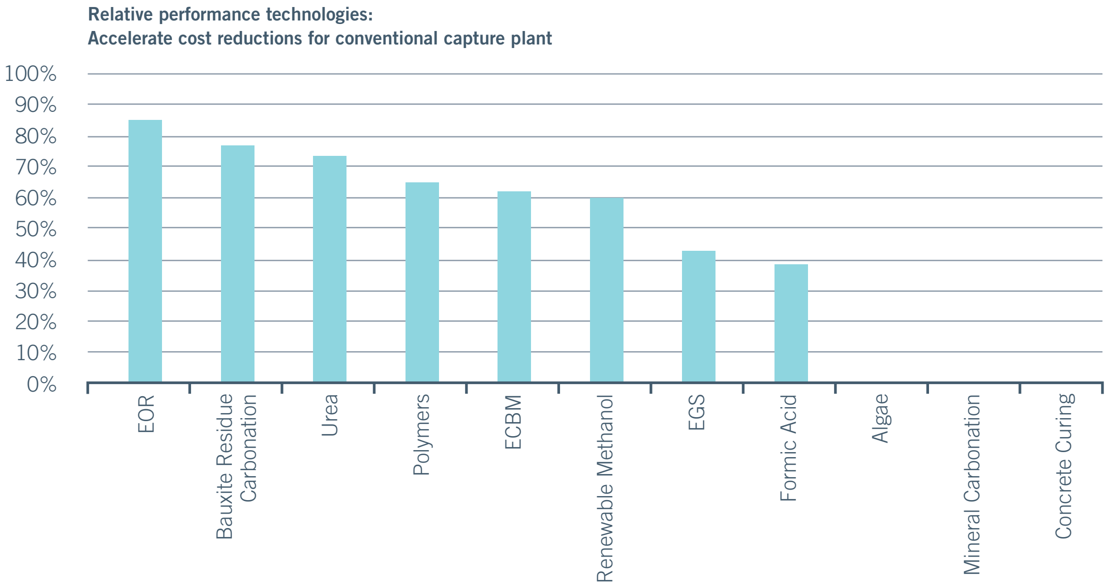
If some of these projects face obstacles in developing the storage component of the project, a reuse technology can provide revenue to offset some of the capture costs and/or the carbon price, to allow the project to proceed. However, for CCS project developers to consider reuse options during the project development process, the reuse technology needs to be proven as commercial within the next five years, and any commercial risks must be understood. In the context of the scoring system both 'technology maturity' and 'commercial viability' criteria are critical and therefore received a high weighting. The following weightings are assigned to each criterion to measure the relative performance of each technology to accelerate cost reductions for conventional CO_2 capture plant:

- Technology maturity: 100 per cent
- Scale-up potential: 0 per cent
- Value for money (commercial viability): 100 per cent
- CO_2 abatement potential, environmental and social: 50 per cent

The probability of a carbon capture and reuse project proceeding can only be enhanced by clearly identifiable social and environmental benefits and CO_2 abatement considerations. Consequently this criteria received a weighting of 50 per cent. Scale-up potential is not critical on the basis that the majority of capture plant cost reductions are likely to happen in the short term and therefore received a weighting of 0 per cent.

The performance of the short-listed technologies are presented in Figure 6.1. The technologies are displayed based on decreasing level of alignment with the objective.

Figure 6.1 Potential to accelerate cost reductions for conventional capture plant[3]



EOR stands out as the technology most able to provide the revenue that might facilitate additional CCS demonstration projects in the short term, which is the period most critical to capture cost reductions.

Beyond EOR, the technologies identified as most promising in the context of accelerating cost reductions for the CO_2 capture plant are: bauxite residue carbonation, urea yield boosting, polymer processing and enhanced coal bed methane recovery.

CO_2 capture plants at urea production plants have been installed by Mitsubishi Heavy Industries in recent years (e.g. Malaysia, 200tpd , commenced operation in 1999; India, 2 x 450tpd, commenced operation in 2006) and a number of additional CO_2 capture plant for urea projects are under development. All of these projects capture the flue gas from the steam reformer, usually natural gas fired. Further opportunities for capture plant retrofits are expected, however their typical unit size (limited by the amount of CO_2 needed to react with the surplus ammonia) is only equivalent to capture of a 20MW to 50MW slipstream from a coal-fired power station. This size limitation is likely to minimise the potential for transferring lessons learned to large scale (multi-hundred MW capacity equivalent) capture plant, consequently limiting the beneficial impact that can be delivered in the form of cost reductions for capture plant.

This limitation also applies to bauxite residue carbonation, which only requires CO_2 equivalent to a 4MW slipstream from a coal-fired power station for every 1Mtpa of bauxite residue generated (dry weight). Considering the scale of typical refinery operations, this would limit capture unit size requirements to less than 20MW equivalent in most locations. It is also expected that the price receivable for CO_2 for bauxite residue carbonation will be very modest.

There are some questions around the commercial viability of ECBM technology even with a relatively low CO_2 value. Pilot studies suggest that the relative adsorption performance of CO_2 and CH_4 means

3 Algae cultivation, mineral carbonation and concrete curing technologies are not applicable as these three reuse technologies generally utilise untreated flue gas directly.

that with a CO_2 price of only US$20/t, the purchase cost of CO_2 would consume US$2/GJ of the gas price. On the other hand, ECBM has large scale potential. Using Queensland, Australia as a case study (selected based on the strong coal seam gas industry in operation), annual storage capacity could nominally amount to 12Mtpa of CO_2 by 2015, which in theory could facilitate large scale (e.g. multi-hundred megawatt) capture demonstration projects.

It should be noted that N_2 can also be used for ECBM, though the methane release mechanisms differ between N_2-ECBM and CO_2-ECBM. Direct flue-gas utilisation is being investigated for ECBM, and if this becomes the preferred approach, conventional capture plant would not be required for ECBM reuse. Hence ECBM technology would not help to accelerate cost reductions of CO_2 capture plants.

In summary, of the top five ranked technologies EOR is likely to have the greatest impact in accelerating cost reductions for capture plants. Bauxite residue and urea yield boosting may also contribute, however they will be limited by the scale of operation. The availability of low-cost high-concentration CO_2 sources in regions with EOR potential will influence the extent to which EOR reuse operates to drive the development of capture plant for high-cost sources such as power, steel and cement plants. With existing global low-cost capacity of around 500 million tonnes annually, it is likely that these sources will account for a large proportion of the supply to meet the demand of an expanding EOR industry.

6.1.2 OBJECTIVE B: ACCELERATE THE UPTAKE OF ALTERNATIVE FORMS OF CCS

Mineralisation technologies (mineral carbonation and concrete curing) have been identified as the technologies best placed to accelerate alternative forms of CCS. EOR is also likely to play an important role.

To measure the capability of the short-listed technologies to accelerate the uptake of alternative forms of CCS the technology the following issues should be considered;

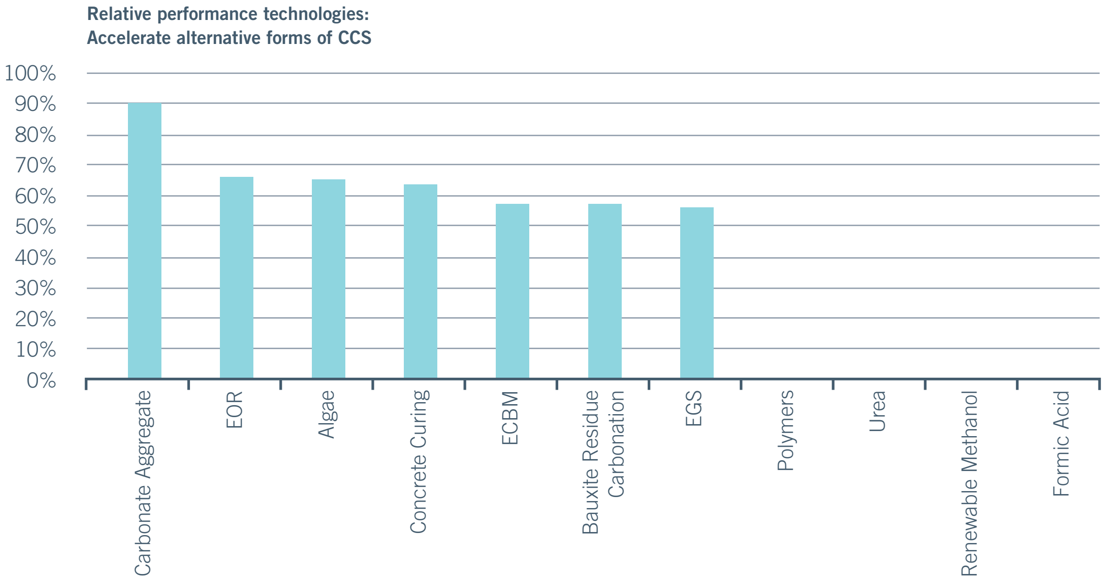
a. The reuse technology should provide permanent storage.
b. The technology should have a high probability of commercial viability in order for uptake of the technology to be realised. The technology needs to be relatively mature within the CCS deployment time scale. However technologies that provide storage will only become more attractive over time once a carbon price is imposed. Technologies with greater scale-up potential may be considered more attractive, but since this may be offset by limits on commercial viability, it is a secondary consideration.
c. The probability of any reuse project proceeding may be enhanced by clearly identifiable social or environmental benefits.

In light of the above, the following weightings assigned to each criterion to measure the relative performance of each technology:

- Technology maturity: 50 per cent
- Potential for scale-up: 50 per cent
- Value for money: 100 per cent
- Permanence of storage (Sub-criterion 4.01): 100 per cent
- Environmental and social (Sub-criteria 4.03 and 4.04): 50 per cent

The results of this scenario are presented in Figure 6.2. The chart displays the technologies in decreasing level of alignment with the objective.

Figure 6.2 Potential to accelerate alternative forms of CCS



The top five performing technologies that may accelerate alternative forms of CCS consist of two of the three alternative embodiments of mineralisation (mineral carbonation and concrete curing), and the two 'enhanced fossil fuel' recovery methods – EOR and ECBM.

Mineral carbonation mineralisation performance is strong based on the following reasons:

- storage has high reliability of permanence and is verifiable.
- commercial viability is a realistic prospect.
- some ancillary benefits can be expected.

A concern with the mineralisation technology is that a readily available alkaline brine resource is a necessity to avoid high energy consumption and a potential increase in net CO_2 emissions. (The scoping LCA results shown in Table 4.3 only present the best case scenario for carbonate mineralisation). Essentially, carbonate mineralisation is valid as an alternative form of CCS. However, it may only result in a net CO_2 emissions reduction solution in very specific circumstances.

The measure for this objective does not give a strong weighting to scale, as it is focused on accelerating alternative CCS in the short-term, during which time limits to scale are not likely to be reached. However, mineralisation in all of its embodiments probably represents the greatest theoretical potential for scale-up of all the reuse technologies because of the advantages mentioned above.

It should be noted that algae cultivation is included in this analysis in the context of potential production of biochar from the algae meal as a coproduct of any liquid fuel. Biochar when applied to soil can improve crop yields, improve fertiliser use efficiency and water retention, and encourage microbial activity, as well as storing carbon. Although research continues on the topic of the stability of biochar in soils, there is evidence to support the thinking that biochar provides long-term storage of carbon.

It is recognised that significant debate still surrounds issues regarding the level of abatement of CO_2, carbon liabilities associated with EOR and the emissions due to combustion of additional fossil fuel products liberated by virtue of the CO_2-EOR. Nonetheless, in a lot of circumstances there are reasonable arguments to say that using CO_2 for EOR constitutes a legitimate avoided emission. For example, if natural CO_2 could be used for the same purpose, then use of anthropogenic CO_2 instead would represent a real decrease in CO_2 emitted to the atmosphere. The emissions from combustion of the fossil fuel are going to eventuate as long as they are extracted. The same can be said for situations where nitrogen or water flooding of oil reservoirs is viable.

Furthermore, the same argument can be applied to ECBM – where nitrogen ECBM would be conducted usually, and hence the use of CO_2-ECBM as an alternative would result in a real decrease of CO_2 emitted to the atmosphere.

6.2 SUMMARY OF PERFORMANCE AGAINST OBJECTIVES

EOR is the reuse technology that is most likely to meet the objective of accelerating cost reductions for conventional capture plant on a scale commensurate with existing stationary power generation. Mineral carbonation mineralisation is well placed to accelerate 'alternative CCS', though this is valid only in ideal circumstances when natural alkaline brine is available. EOR is also likely to play an important role, if it is viewed as permanent storage under an emissions trading scheme.

From the above analysis, the top five performing technologies for each objective are summarised in Table 6.1.

Table 6.1 Top five performing technologies for each objective

OBJECTIVE: ACCELERATE COST REDUCTIONS FOR CONVENTIONAL CAPTURE PLANT	OBJECTIVE: ACCELERATE ALTERNATIVE FORMS OF CCS
EOR	Mineral carbonation
Urea yield boosting	EOR
Bauxite residue (red mud) carbonation	Concrete curing
Polymers	Algae cultivation
ECBM	ECBM

Of the technologies requiring relatively high purity CO_2, it has been identified that relatively small demand can be expected from a single production facility for urea yield boosting (<50MW coal-fired power station slipstream equivalent), for bauxite residue carbonation (<20MW) and for renewable methanol (currently <1MW). As a result, only EOR remains as the reuse technology that is able to meet the objective of accelerating cost reductions for conventional capture plant on a scale commensurate with existing stationary power generation. ECBM is at an early stage of development and further research and trials are required to establish whether ECBM can be developed so that the benefits outweigh the offsets.

Carbonate mineralisation is well placed to accelerate 'alternative CCS', though a concern with mineralisation is that a readily available alkaline brine resource is a necessity in order to avoid high energy consumption and a potential increase in net CO_2 emissions. EOR is likely to play an important role, although it is affected by the fact that additional emissions will result from the additional oil that is recovered. It is not clear how this will be viewed under an emissions trading scheme. When biochar is produced from algal meal, algal bio-fixation also provides an alternative form of CCS, though the overall economics of biochar utilisation, the permanence of its storage and its position under emissions trading schemes remains to be firmly established.

PART 2
ECONOMIC AND COMMERCIAL EVALUATION

1. CONTEXT

Part 1 of this report focuses in detail on the short-listed CO_2 reuse technologies, so that the characteristics of each technology are thoroughly understood. An in-depth understanding of the technologies is a prerequisite for determining their overall potential to accelerate the uptake of CCS.

Part 2 of this report takes a step back from the detailed technology evaluation and considers the broader economic and commercial framework for CO_2 reuse, with the aim of exploring the question:

How can CO_2 reuse accelerate the uptake of CCS?

In order to explore this question, it is fundamental to understand:

- The current CO_2 market – the supply/demand balance, and the pricing of bulk CO_2; and
- The commercial framework for CCS – considering what carbon emissions pricing or regulatory requirements might be imposed in the future, and how they relate to the costs of CO_2 capture and storage.

Following a review of the CO_2 market and commercial framework for CCS, a number of deployment scenarios are considered. The deployment scenarios consider the technologies by category (as defined in Part 1 – Section 3) and are intended to provide an overview of how the implementation of various categories of CO_2 reuse technologies may accelerate the uptake of CCS.

2. THE CO_2 MARKET

Revenue generated from selling CO_2 for reuse is likely to be moderate, and subject to future downward price pressure because of the strong potential supply surplus.

Understanding the current and future potential CO_2 market size, the CO_2 market price and hence the possible revenue generated from the selling of CO_2 for reuse applications is fundamental in determining the potential impact the short-listed technologies may have in accelerating the uptake of CCS.

The current global CO_2 demand is estimated to be 80 Mtpa, of which 50Mtpa is used for EOR in North America. The future potential demand for CO_2 that could eventuate by 2020 is estimated to be 140Mtpa, taking into consideration the current development status of the short-listed reuse technologies. The current and future potential CO_2 demand are immaterial when compared to the total potential CO_2 supply from large point sources, which is estimated at 500 million tonnes annually for high-concentration sources, and 18 gigatonnes per annum (18000Mtpa) of dilute CO_2 from power, steel and cement plants.

Due to this supply surplus, large scale facilities such as power, steel and cement plants that install CO_2 capture, and natural gas processing plants which produce CO_2 as a by-product of their operations, are likely to be price-takers in the market for CO_2, particularly under regimes that impose a carbon price penalty on emissions. The likelihood of a growing global CO_2 supply surplus is consistent with an expectation that bulk CO_2 market prices for reuse applications will be no higher than at present, and that they will be subject to future downward pressure that will strengthen with the adoption of regimes that impose a carbon price penalty on emissions.

2.1 DEMAND

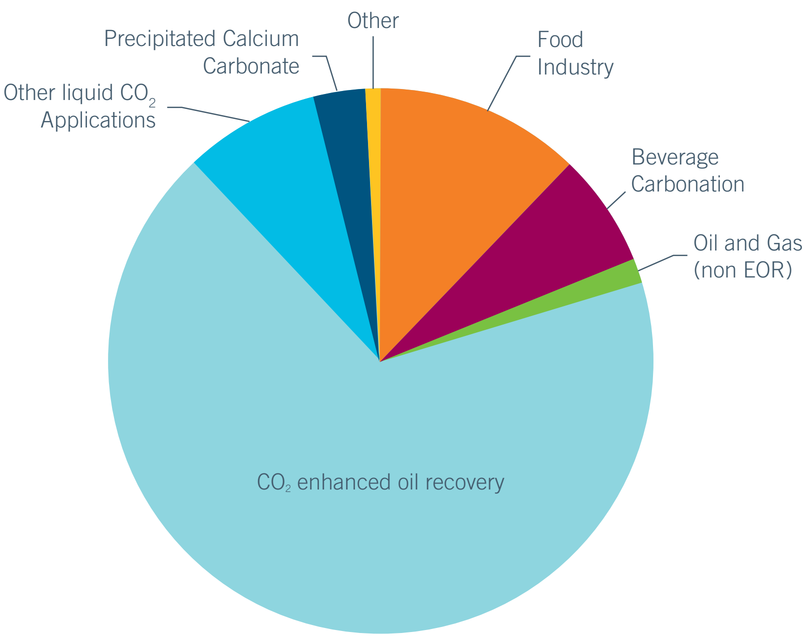
2.1.1 CURRENT DEMAND

As presented in Part 1, currently there are a large number of uses for CO_2. Despite the large number of uses identified, many are on a relatively small scale. The picture of current CO_2 utilisation on a scale relevant to the use of CO_2 captured from large point source emitters is presented in Figure 2.1. This is based on the following data:

- The current global demand for CO_2 is estimated at 80Mtpa.
- Of this 80Mtpa, at least 50Mtpa is utilised for EOR, almost exclusively in North America.
- The remaining 30Mtpa represents the global demand of all other uses, predominantly the mature industries of beverage carbonation and food industry uses.

Note that the numbers above represent non-captive uses for CO_2; captive uses are not considered. Refer to Section 2.4 for more details on the distinction between captive and non-captive uses for CO_2.

Figure 2.1 Approximate proportion of current CO_2 demand by end use



2.1.2 FUTURE DEMAND

The future potential demand for CO_2 that could eventuate by 2020 was estimated, taking into consideration the current development status of the short-listed reuse technologies. The estimates for the cumulative demand to 2020 were presented and discussed in Part 1 of the report. The future demand estimate (for the year 2020) for the short-listed reuse technologies is 140Mtpa, including EOR. This estimate is based on a predicted growth of current technologies such as EOR and urea fertiliser and the implementation and commercialisation of demonstration projects for the remaining technologies in line with their prospective development timeframes.

2.2 SUPPLY

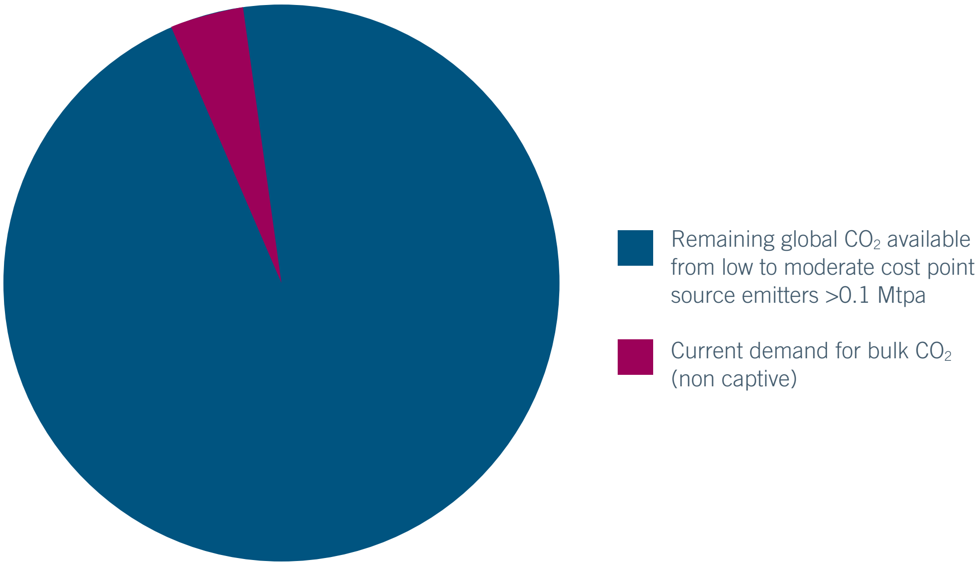
The estimated current global demand of 80Mtpa is supplied from natural geological CO_2 reservoirs, or is produced as a by-product from several different industrial processes such as ammonia production, ethanol production, and natural gas processing. This bulk CO_2 is sold to the industrial gas industry, or in the case of gaseous CO_2 for EOR (enhanced oil recovery), is supplied to the oil and gas sector through dedicated pipelines.

Over 80 per cent of the CO_2 used for EOR in the US is sourced from natural wells, and by default this CO_2 from natural sources represents the majority of the world's non-captive CO_2 supply. There is a good opportunity to extensively replace the natural CO_2 with anthropogenic CO_2 for applications such as EOR. The total potential CO_2 supply from large point sources (greater than 0.1Mtpa from a single site) is estimated at 18 gigatonnes per annum (18000Mtpa). The cost to capture CO_2 varies amongst the different sources that make up this 18Gtpa. For example, capture of CO_2 from power generation plants is expensive, yet this makes up over 70 per cent of the 18Gtpa from large point source. However, the cost to capture from sources that are currently typically utilised (e.g. CO_2 from ammonia plants, ethanol production, natural gas processing) is relatively low cost.

Data concerning the amount of CO_2 available from each source is not exact. However, by consideration of the IPCC Special Report on CCS (2005) and the IEA's CO_2 Emissions Database (courtesy IEA Greenhouse Gas R&D Programme), it is estimated that the lowest cost sources could provide 500Mtpa or more of CO_2, with low-intermediate cost CO_2 sources (<US$35/t CO_2 avoided) providing another 2Gtpa plus.

The current demand for CO_2 is shown relative to the potential supply from these low-intermediate cost sources in Figure 2.2 below.

Figure 2.2 Current global CO_2 supply and demand



It is evident that there is a very large theoretical supply surplus. The demand estimated for 2020 (140Mtpa as compared to the current 80Mtpa for the short-listed technologies) does not make a significant difference in this supply-demand balance. Even taking into account very optimistic scenarios for the uptake of CO_2 reuse technologies in the next decade, the supply surplus is likely to grow with the adoption of regimes to restrict CO_2 emissions.

It is also evident that the large volume of CO_2 available from low to medium cost sources is likely to supply the majority of near-term reuse demand growth in preference to higher cost supply that could be developed by installing capture plants on power, steel or cement plants.

2.3 CO_2 MARKET PRICING

2.3.1 PRICING OF BULK CO_2

The price of bulk CO_2 is typically agreed through private negotiations between parties and is not generally available for public scrutiny. However, the following are examples of known prices:[4]

- Ammonia producers in the US experienced a range in prices of around US$3 to US$15 per metric tonne for bulk gaseous/supercritical CO_2, which varied significantly by location within the US.
- The price for pipelined CO_2 has historically been in the range of US$9-US$26 per tonne, which incorporates the cost of the pipeline infrastructure (capital and operational costs).
- The Dakota Gasification Company's Great Plains Synfuels Plant pipes CO_2 205 miles to Canada. In 2009 they sold US$53.2m worth of CO_2, whilst it produced 2.8Mtpa, suggesting a price of US$19 per metric tonne produced, incorporating the cost of transportation – although only half their emissions were consumed.
- Cardinal Ethanol LLC, who in March 2010 entered into a contract to sell 40,000 tonnes of CO_2 at a price of US$5/tonne. The recipient of the CO_2 pays for the transportation.

The range of prices above is considered a realistic representation of the bulk gaseous/supercritical CO_2 price in the present, and to represent a general upper limit into the future.

In summary, large scale facilities such as power, steel and cement plants that install capture technology, and natural gas processing plants which produce CO_2 as a by-product of their operations, are likely to be price-takers in the market for CO_2. This is due to the aforementioned supply surplus and the prospect of regulatory constraints on CO_2 emissions.

2.3.2 FUTURE PRICING OF BULK CO_2

Since the current supply surplus is likely to increase in the future, the current market prices for bulk CO_2 are indicative of the upper limit of prices that can be expected into the future.

4 SRI Consulting, March 2010, Chemical Economics Handbook 2010

3. FRAMEWORK FOR CCS

A carbon price or equivalent mechanism will have a positive impact on the economics of CCS.

For CCS from power generation, a strong carbon price and improved capture costs will be required to make CCS viable. Initial CCS demonstration projects for power generation will require public funding in addition to any carbon price that is likely to prevail in the near-term.

For CCS from natural gas processing (low cost capture), current carbon prices under schemes such as the European Union Emissions Trading Scheme are not far short of the level necessary to trigger CCS.

It is generally agreed that CCS is an essential component of a portfolio of technologies and other measures to reduce greenhouse gas emissions. Despite this long term requirement for CCS, it is currently only commercially viable for gas processing and EOR-supported projects and remains some way off commercial viability for the power generation, steel and cement industries.

Applying CCS technology to industrial processes imposes additional capital and operating cost penalties when compared to the same process without CCS. The viability of these CCS technologies depends on the existence of either a sufficiently strong price signal or a regulatory obligation or both. The initial demonstration projects will also require substantial public funding to overcome the first-of-a-kind cost and competitive disadvantage. A high-level description of the possible commercial framework applying to CCS is given below.

3.1 NO PRICING OF CO_2 AND NO REGULATORY OBLIGATION

At present, in most countries outside Europe, CO_2 emissions do not incur a cost and there are no regulatory obligations to capture and store CO_2. In the absence of either a price signal or a regulatory obligation there are very limited drivers for private companies to invest in a process that does not give defined benefit and only serves to increase their cost base and reduce competitiveness.

There are potentially CO_2 reuse technologies (such as EOR) which will facilitate and support CCS projects becoming commercially viable, whilst also providing long term storage. It is therefore possible that some capture and long term storage of CO_2 will emerge (and has already been implemented) based heavily on commercial drivers. However, CCS already implemented due to commercial drivers has relied on CO_2 sources where capture costs are low when compared to the forecast costs for capture from power generation.

3.2 PRICING OF CO_2 EMISSIONS

CCS reduces CO_2 emissions vented to the atmosphere. This creates a cost saving where the emission source is covered under an emissions trading scheme such as the European Union Emissions Trading Scheme (EU ETS), and provided the cost of CCS is less than the price penalty imposed on emissions.

The sources covered under an ETS are typically large point sources with material CO_2 emissions. For example, the EU ETS covers around 11,000 installations in power generation and other industries (oil refineries, coke ovens, iron and steel plants, factories making cement, glass, lime, brick, ceramics, pulp and paper). From 2012, the EU ETS will also include civil aviation, and from 2013 it will include manufacturing of aluminium and certain basic chemicals.

Most other ETS's in place or under development have a similar focus on large point sources of CO_2 emissions. In addition, some countries (such as Norway) have used domestic taxes that have a similar impact to an ETS through pricing CO_2 emissions.

Where a point source is covered under an ETS (or a tax) the viability of CCS depends on the benefits of reduced CO_2 emissions in comparison with the cost of CCS technologies. In simple terms, if it is cheaper to capture and store than to emit CO_2, then CCS technologies should be viable.

In most cases where CO_2 is priced the price remains too low to make CCS technologies viable at their current stage of development. This is particularly true of power generation with CCS due to the relatively high costs of capture.

Current estimates of the cost per tonne of CO_2 avoided are given in the Global CCS Institute foundation report Economic Assessment of Carbon Capture and Storage Technologies (2011 Update). The cost per tonne of CO_2 avoided is based on comparison against a reference plant for the same product. The analysis shows the following costs per tonne of CO_2 avoided, once the relevant technology is mature (and so Nth-of-a-Kind or NOAK costs):

- US$44 to US$103 for power generation technologies. Post-combustion technologies, the dominant current technology, has costs in the range US$57 to US$78.
- US$49 for cement and US$49 for steel production.
- US$20 for fertiliser production and US$19 for natural gas processing.

The EU ETS is currently the largest and most liquid carbon market. The price under the EU ETS has been volatile and is currently around EUR15/tonne (US$18 based on a foreign exchange rate or EUR1 = US$1.2). This indicates that CCS costs for power generation are well in excess of carbon prices currently or in the near future.

This analysis also suggests that CCS for natural gas processing and fertiliser production will be closer to viability if these processes are covered under an ETS or some other mechanism for pricing emissions. Sleipner and Snohvit provide examples of installing and operating CCS in response to price signals on the cost of CO_2 emission, although in this case a tax rather than the EU ETS.

The evidence is therefore that pricing of CO_2 emissions can have a positive impact but is currently unlikely to be sufficient to provide incentive for widespread incorporation of CCS within power generation, steel making and cement making unless there is a significant increase in carbon prices and/or a reduction in CCS costs.

3.2.1 REGULATORY OBLIGATIONS TO CAPTURE AND STORE CO_2

In addition to price signals under an ETS, it is possible to impose CCS obligations through mechanisms such as planning consents, major project approvals, operating licences and other mechanisms.

Compliance with a regulatory obligation will also impose significant capital and operating costs. The impact of imposing these additional costs will depend on the viability of the project:

- In some cases the benefits will justify the additional costs of complying with CCS regulations and the project will proceed. A recent example is the Gorgon project in Western Australia. The significant revenues associated with natural gas production from the Gorgon field mean that the project appears to remain viable with the additional costs associated with incorporating CCS. As noted, the additional costs for natural gas processing are lower than for power generation, increasing the prospects of viability. In other cases the impact of regulatory obligations may mean that projects do not proceed. For example, the UK Government has introduced an obligation that new coal-fired power generation include CCS for sent-out capacity of 300 MW. This will only be commercially viable if coal-fired generation with CCS is competitive against the costs of other generation technologies such as (unabated) CCGT, nuclear and renewable generation.

The evidence shows that regulatory requirements can either promote CCS, where the project remains viable when these costs are included, or defer or prevent projects when the project is not viable when the costs of complying with regulation are included.

3.2.2 SUMMARY OF PRESENT POSITION

Experience to date indicates that in the absence of substantial public funding, large scale demonstration of CCS is likely to be restricted to projects analogous to those already in operation – that is where low cost CO_2 sources such as gas processing can be combined with storage that yields some kind of benefit such as EOR. High cost sources such as the capture of CO_2 from power generation and steel making are unlikely to be commercially viable under current conditions where:

- price signals are either non-existent or too low to cover the full costs of power and industrial CCS; and, or
- regulatory mechanisms may prevent the development of unabated technologies but in many cases will not make CCS viable in competition with other technologies which do not bear similar cost penalties.

This conclusion is also reflected in other recent studies. For example, the IEA report states:

"A financial gap exists as a result of the additional costs for CCS above a conventional plant being higher than the revenue from the relevant market plus the additional benefit from CO_2 reduction. This gap will decline as experience with the technology increases resulting in cost reduction, and as the revenue from the relevant market and the benefit for CO_2 reduction increases."[5]

In summary, the principle impediment in the adoption of CCS for power generation, steel and cement making is the present high cost of capture. However, the adoption of CCS regarding gas processing and fertiliser production appears more favourable, given the lower capture costs.

5 IEA/CSLF report to the Muskoka 2010 G8 Summit, page 7

4. ROLE OF CO_2 REUSE IN FACILITATING CCS

This section considers a number of case studies to determine the role of CO_2 reuse in facilitating CCS. The case studies consider the technologies by category (as defined in Part 1 – section 3) with a focus on answering the following pertinent questions:

- How beneficial is CO_2 reuse as a transitional measure to CCS?
- To what extent might the implementation of CO_2 reuse technologies bring forward the date at which high-cost forms of CCS such as power generation become viable?

This section is segregated into two parts. Section 4.1 provides an understanding of the key costs and revenues associated with CCS, while section 4.2 reviews a number of development scenarios based on varying market assumptions and examines the overall impact that CO_2 reuse technologies may have on the deployment of CCS.

4.1 KEY COSTS AND REVENUES ASSOCIATED WITH CCS

As discussed in section 3, there is a significant funding gap in large scale demonstration of the high-cost forms of CCS, such as power generation and steel and cement making. The largest element of the costs for CCS with power generation and steel and cement making is the capture plant. The following discussion focuses on carbon capture from power generation (a major CO_2 source for which carbon capture needs to be demonstrated at commercial-scale), but will also consider carbon capture from other industrial sources that may have lower capture costs than for power generation. The lower costs for capturing CO_2 from industrial sources are due to the relatively high concentration CO_2 stream from gas processing and fertiliser plants when compared to emitted gases from power generation and steel and cement making.

The success of CO_2 reuse technologies in facilitating CCS will be affected by the outcomes of the following three questions:

- What is a realistic level of revenue to be expected from the sale of CO_2 for reuse?
- How much does CCS cost now, and how much will it cost in the future?
- What is the carbon price expected to be in the future?

These questions have been addressed in the previous sections, however they are summarised and detailed below as necessary.

4.1.1 WHAT IS A REALISTIC LEVEL OF REVENUE TO BE EXPECTED FROM THE SALE OF CO_2 FOR REUSE?

The 2009 price of gaseous CO_2 for EOR (US$19/t) and the high end of the price range for CO_2 from ammonia plants (US$15/t) are considered to be indicative of the upper end of realistic future revenue from the sale of CO_2 reuse.

As per Section 2, there is presently a significant general supply surplus which is likely to remain in the future and consequently revenue from the sale of bulk CO_2 will be relatively low. The 2009 price of gaseous CO_2 for EOR (US$19/t) and the high end of the price range for CO_2 from ammonia plants

(US$15/t) is considered indicative of the upper end of realistic revenue from the sale of CO_2 for reuse. These levels of revenue will be used as the basis for the development scenarios later in this section.

4.1.2 HOW MUCH DOES CCS COST NOW, AND HOW MUCH WILL IT COST IN THE FUTURE?

Capture costs are a significant portion of the capital cost of CCS for power generation and for steel and cement making. Emerging technologies typically display improvements in costs as their level of deployment increases. Based on cost reduction estimates of Rubin et al (2007), a plausible experience curve derived for integrated CCS projects indicates a nominal decrease in the costs of power generation CCS from US$81/t CO_2 avoided to US$59/t CO_2 avoided following 10GW of deployment. This experience curve forms the basis for the development scenarios.

As noted in Section 3.2, current estimates of the cost per tonne of CO_2 avoided are given in the Global CCS Institute foundation report Economic Assessment of Carbon Capture and Storage Technologies (2011 Update). The cost per tonne of CO_2 avoided is based on comparison against a reference plant for the same product. The analysis shows the following costs per tonne of CO_2 avoided, once the relevant technology is mature (and so Nth of a Kind or NOAK costs):

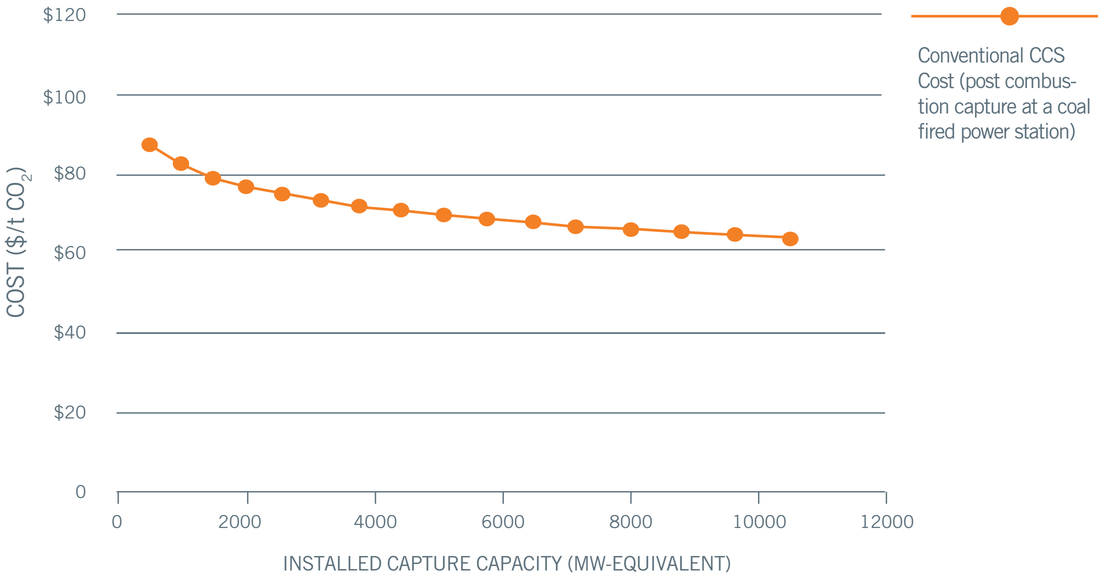
- US$44 to US$103 for power generation technologies. Post-combustion technologies, the dominant current technology, has costs in the range US$57 to US$78.
- US$49 for cement and US$49 for steel production.
- US$20 for fertiliser production and US$19 for natural gas processing.

The Global CCS Institute report also shows that capture costs are a significant portion (~82 per cent) of the capital cost of CCS for an integrated post combustion power plant with CCS. The Global CCS Institute analysis also concludes that there are likely to be high initial contingencies related to both cost and process. Contingencies for early mover projects are estimated at upwards of 20 per cent.

In terms of future costs of CCS, emerging technologies typically display improvements in cost as their level of deployment increases. Each successive plant design benefits from knowledge gained from the deployment of previous plants, such that incremental improvements are continually being made. Naturally improvements are easier to discover whilst the technology is still relatively immature, the rate of cost reduction is initially high but gradually reduces as the technology matures. The resulting characteristic cost reduction curve is referred to as an experience curve.

A plausible experience curve for integrated power generation CCS projects is shown in Figure 4.1. This makes use of the cost reduction estimates of Rubin et al, who developed a rational basis for their estimates by considering historical technology experience curves for relevant technologies including flue-gas desulphurisation, selective catalytic reduction, oxygen production, LNG production, and others. The curve presented is for carbon capture from a coal-fired power station, and shows a nominal 27 per cent decrease in the costs of CCS, from US$81/t CO_2 avoided to US$59/t CO_2 avoided following 10GW of deployment.

Figure 4.1 Plausible CCS experience curve for integrated power generation projects with CCS



The study of Rubin et al is one of a number of studies that examine the impact of learning on cost reduction for new technologies. The Global CCS Institute analysis has also indicated the possible nature of improvements to generation and capture technology. Changes in capture technology, or improvement in performance of existing mature technologies, can reduce the high energy demand for current technologies and their cost impact.

It should be noted that there will always be uncertainty attached to potential cost reductions. Figure 4.1 represents one plausible scenario, however, the real cost reductions achieved could be significantly greater, or significantly less.

4.1.3 WHAT IS THE CARBON PRICE EXPECTED TO BE INTO THE FUTURE?

A carbon price trajectory based on the '450 Scenario' modelled by the International Energy Agency (IEA) is a relatively aggressive scenario and estimates that a global CO_2 price of approximately US$50/t by 2020 and US$110/t by 2030 would be needed to stabilise atmospheric CO_2 at 450 ppm.

Following on from section 2.2, it is assumed that the preferred means of achieving global emissions reductions is through the implementation of a global carbon price. Even if other mechanisms are utilised in the future, they can essentially be reduced to some equivalent carbon price that drives emissions reduction activities.

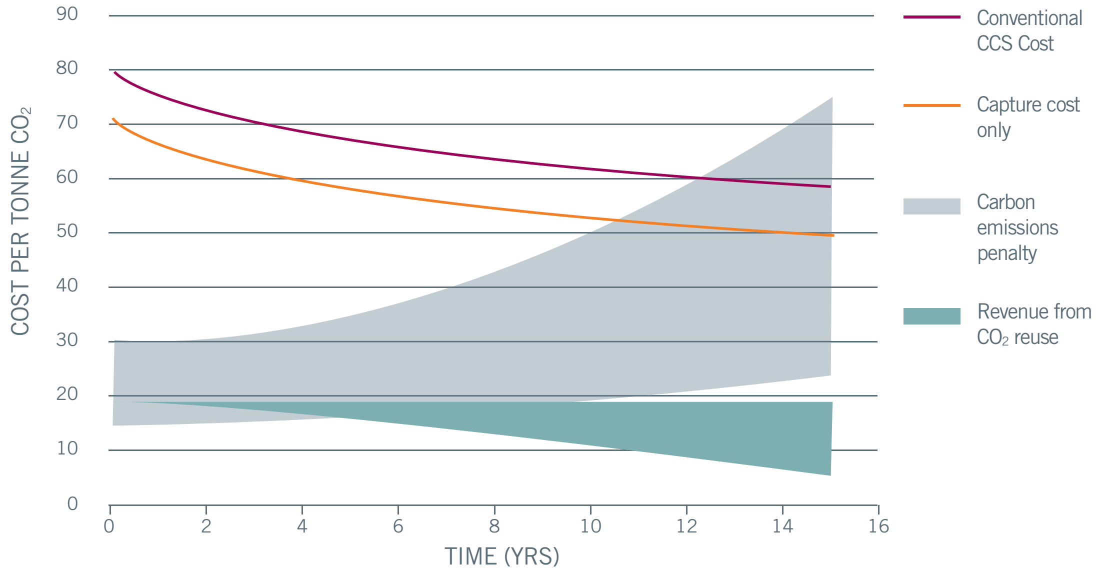
Significant uncertainty surrounds what will be the future carbon price trajectory. For the purposes of the development scenarios that follow, a carbon price trajectory based on the '450 Scenario' as modelled by the International Energy Agency is assumed, which indicates global CO_2 pricing required to restrict atmospheric CO_2 concentration to no greater than 450ppm. The '450 Scenario' estimates that a global CO_2 price of approximately US$50 / tonne by 2020 and US$110 / tonne by 2030 would be required to achieve the 450ppm target.

The '450 Scenario' could be considered a relatively ambitious scenario, with a relatively rapid rise in carbon price that governments may find difficult to adopt. However, it is important to note that less aggressive assumptions on carbon price will not affect the conclusions of this section, other than stretching the graphs over a longer timeline. The conclusions would generally be unaltered.

4.2 INTERACTION OF KEY COSTS AND REVENUES

A graphical representation of the key costs and revenues associated with CCS and CO_2 reuse is presented in Figure 4.2.

Figure 4.2 Interaction of key costs and revenues



The graphical representation above shows the relativity between the carbon price trajectory, the cost of conventional CCS for power generation, the cost for capture-only, and the potential revenue from CO_2 reuse. The interactions between these variables is complex; the graph is only intended to demonstrate the upper and lower limits of each variable and to give an indication of the relative impact of carbon price and reuse revenues on CCS costs.

The grey shaded area on the graph represents the potential carbon-price over the period, bounded by the 450 Scenario (upper line) and an alternative scenario in which the CO_2 price is weaker (lower line). The carbon-price will depend on a number of variables such as national and international emissions limits, and the implementation of effective regional & global CO_2 markets, and so is difficult to predict. For this reason, it is shown as a wide range. It is assumed that the carbon-price will grow in the long term and so is shown as a general upward trend.

Potential revenues for reuse are shown in blue. The revenue from reuse at the outset is assumed to be US$19/t which is equivalent to the current typical revenue from EOR. Over time, reuse revenues are expected to fall as the carbon-price increases and there is greater incentive to capture and either store or reuse CO_2. In this environment, CO_2 is expected to become a surplus commodity, which in turn will exert a downward pressure on the bulk CO_2 price. As such the reuse revenues are shown as a general downward trend.

It should be noted that the revenue from reuse is modest, relative to the costs of CCS and therefore reuse will at best provide only a moderate offset to the costs of capture.

The point at which the cost for CCS (magenta line) and the carbon-price (grey) intersect, is the point at which it becomes more economical to implement CCS, than to continue to pay the carbon-price. At this point, CCS can be said to be commercially viable.

From the graph it can be concluded that, at current technology maturity levels, a strong carbon price is key to the acceleration of CCS. Reuse revenues will by contrast, only provide a modest offset to the costs, and cannot be considered to be a commercial driver of CCS.

4.3 DEVELOPMENT SCENARIOS

Four scenarios for the future reuse of CO_2 are discussed. These scenarios consider a growing carbon price (weak to strong), and also how effectively each technology will permanently store CO_2. These factors have a significant bearing upon the potential impact of reuse technologies to accelerate CCS deployment and are described below:

A weak carbon pricing scenario represents a world where carbon pricing is localised and inadequate to materially restrain either global CO_2 emissions or the growth in fossil fuel consumption. Its implications include relatively weak growth in the availability of captured concentrated CO_2 for reuse or conventional storage, and relatively strong growth in the demand for CO_2 use in EOR and possibly in other forms of enhanced fossil fuel production. It is a world where the pricing of CO_2 for reuse remains at the upper end of the current price range.

A strong carbon pricing scenario represents a world where carbon pricing is sufficiently widespread and substantial to materially restrain global CO_2 emissions and the growth of fossil fuel consumption. Its implications include relatively strong growth in the availability of captured concentrated CO_2 for either reuse or conventional storage, and relatively moderate growth in the demand for CO_2 use in fossil fuel production. It is a world in which there is a strong downward pressure on CO_2 prices, caused by a surplus of bulk CO_2 captured from point sources.

CO_2 reuse technologies that permanently store CO_2 include carbonate mineralisation, CO_2 concrete curing, bauxite residue carbonation, and ECBM, with EOR likely to be considered storage when appropriate MMV programs are in place. Carbonate mineralisation and CO_2 concrete curing use flue gas directly, whereas EOR and bauxite residue carbonation require a concentrated CO_2 stream. CO_2 reuse technologies that permanently store CO_2 can be considered a complement to conventional sequestration, since they can provide long-term CO_2 abatement.

Reuse technologies that temporarily store CO_2 are those with end products that release the CO_2 again when they are used. They include urea yield boosting, renewable methanol and other liquid fuel production, and food and beverage industry uses of CO_2. Their emissions mitigation credentials are limited, and are generally restricted to those indirect circumstances where anthropogenic CO_2 replaces naturally occurring reservoir CO_2 in the process, or where the end product replaces a product which would otherwise be sourced from fossil fuels. For example, it could be argued that the use of anthropogenic CO_2 in the enhanced production of algal biofuels has a mitigation effect stemming from the replacement of fossil fuels even though the anthropogenic CO_2 is released to the atmosphere when the biofuel is used.

4.3.1 DEVELOPMENT SCENARIO 1 – WHEN A STRONG CARBON PRICE IS IN PLACE, WHAT BENEFIT WILL CO_2 REUSE PROVIDE WHEN THE REUSE PERMANENTLY STORES CO_2?

With a strong carbon price, reuse technologies which permanently store CO_2 (e.g. carbonate mineralisation, CO_2 concrete curing, bauxite residue carbonation, ECBM and EOR) will be attractive because they can simultaneously provide revenue and avoid carbon emissions (thereby reducing exposure to the carbon price). However, with a strengthening carbon price, a downward pressure on the bulk CO_2 price is expected and therefore the revenue to be derived from selling CO_2 for reuse is likely to be minimal (as shown in Figure 4.2). Reuse would be viable only where it provides a lower cost disposal option than conventional geological storage.

In the near term (e.g. during the time period in which CCS must be demonstrated) it is unlikely that strong carbon pricing will be observed, and as a result it will not act as the driver for demonstration CCS projects. The funding shortfall will instead be met by government funding, contributions from project proponents, and other funding bodies. Reuse revenues in the near term will not be a primary driver for demonstration projects. However, where demonstration projects do proceed, reuse revenues can act as a moderate offset to CCS costs. In reality EOR is likely to be the key contributing reuse technology due to its maturity and capacity for CO_2 utilisation. This is supported by the fact that many of the presently proposed CCS demonstrations intend to supply CO_2 for EOR.

In the long-term, CCS deployment will only be driven by a strong carbon price and reuse revenues will likely be subjected to downward pressure from a surplus of bulk CO_2.

Reuse technologies which do not require a concentrated CO_2 stream (e.g. carbonate mineralisation) may have significantly lower capture costs, and are likely to have a positive impact on advancing the demonstration of alternative forms of CCS, providing that the technologies are at a suitable level of maturity.

The recognition of the abatement credentials for reuse is critical to the uptake and growth of reuse technologies. For instance, the application of enhanced fossil fuel production (EOR, EGR, ECBM) requires MMV validation of storage permanence, and regulatory acceptance that the storage mitigation effect is not offset by the additional emissions arising from enhanced fossil fuel production.

Provided that their abatement credentials are recognised, permanent storage reuse technologies may have a niche role where their net cost is less than the net cost of conventional geological storage or the net cost of paying the carbon price for emitting the CO_2 to the atmosphere.

Overall mature CO_2 reuse technologies such as EOR can play a useful role in supporting early CCS demonstration, but as the surplus of available CO_2 grows and as the longer term bulk CO_2 market price weakens, the scope for EOR and the longer-term permanent storage technologies will depend on recognition of their mitigation credentials and their cost competitiveness relative to alternative mitigation options.

4.3.2 DEVELOPMENT SCENARIO 2 – CAN A CO_2 REUSE TECHNOLOGY THAT DOES NOT PERMANENTLY STORE CO_2 BECOME COMMERCIALLY VIABLE WHEN A CARBON PRICE IS IN PLACE?

CO_2 reuse technologies that do not permanently store CO_2 include urea yield boosting, renewable methanol and other liquid fuel production, and food and beverage industry uses, amongst others. Since this development scenario focuses on the sale of CO_2 to reuse technologies that do not permanently store CO_2, the resultant net cost will depend on:

- the structure of the particular emissions trading or taxation system that is in place
- the approach taken to carbon liabilities (e.g. whether the carbon price is passed on to the end product of CO_2 reuse or remains with the original CO_2 source/emitter), and
- whether the end use for the CO_2 remains competitive with non-carbon based alternative products. Competition may restrict the extent to which any carbon price can be borne by the end product of reuse.

With a strong carbon price and surplus supply of CO_2, the key issue governing the uptake of these technologies is the extent to which they are accepted as having an abatement effect and are validated as an emissions offset. This suggests that with a weak bulk CO_2 market price for reuse, the prospects for reuse technologies that provide only temporary storage are very uncertain.

At face value reuse technologies with only temporary CO_2 storage characteristics have no real prospect of being credited with a CO_2 abatement effect. The exception may be where it is accepted that anthropogenic CO_2 used in the reuse technology effectively replaces naturally occurring reservoir CO_2 in the process, or where the end product replaces a product which would otherwise be sourced from fossil fuels. This is a reversal of the logic which would potentially discount EOR for mitigation purposes because it increases fossil fuel production and consumption.

Overall there is very limited potential for reuse technologies where CO_2 storage is temporary in a strong carbon price environment – except in circumstances where regulators accept that the process either replaces natural reservoir CO_2 or the product replaces products derived from fossil fuels.

4.3.3 DEVELOPMENT SCENARIO 3 – CAN CO_2 REUSE TECHNOLOGIES ACCELERATE THE DEMONSTRATION OF INDIVIDUAL ELEMENTS OF THE CCS CHAIN, IN LIEU OF FULLY INTEGRATED DEMONSTRATION PROJECTS?

The G8 target is for 20 CCS demonstration projects operational by 2020. In practice this might mean a cumulative abated capacity of 6GW by 2020. The Global CCS Institute report The Global Status of CCS: 2010 has shown there appears to be enough government funding to support 25 large scale projects globally. Issues and challenges with public acceptance, proving of storage locations, process and planning delays in approvals, or the commercial challenges in developing, completing, negotiating and awarding such complex projects may mean that implementation of the full suite of fully integrated projects may be more protracted than initially thought.

In such circumstances, it is not unreasonable to assume that stand-alone capture plant demonstrations might continue in lieu of fully integrated projects, as governments and operators seek to use the available, committed funding to bridge the CCS knowledge gap where possible. In such a scenario, use of the captured CO_2 would be both logical and economical.

In the case where fully integrated CCS projects are delayed and limited to a small number of projects, reuse technologies that require a concentrated stream of CO_2 (from a conventional capture plant) could act as a demonstration substitute to fully integrated projects to bring forward capture plant cost reduction, capability building, knowledge sharing, and learning. Such a scenario would maximise the cost reductions that are achievable for the capture plant, albeit in a non-integrated project.

4.3.4 DEVELOPMENT SCENARIO 4 – WILL CO_2 REUSE BE COMMERCIALLY VIABLE IN A WEAK CARBON PRICE ENVIRONMENT

If there is a weak carbon price, the revenue generated by selling CO_2 for reuse must be greater than the costs of CO_2 capture in order for it to be considered a commercially viable option. As is demonstrated by Figure 4.2, this is unlikely to be the case.

The permanence, or otherwise, of storage associated with the reuse of CO_2 is less important under weak carbon pricing than the value of the reuse product and the cost competitiveness of the technology in question. For example the use of anthropogenic CO_2 in enhancing the production of algal biofuels would be driven primarily by the value of the biofuel rather than the by the value of its emissions abatement effect.

While the permanence of storage is less of an issue, so too would be consideration of indirect effects on fossil fuel production and consumption. The emissions abatement benefit of biofuels centres on their ability to replace fossil fuels as an energy source, and the value attributed to that benefit will be lower in a world of weak carbon prices. Enhanced biofuels would therefore be less valued for their mitigation effect. Similarly there would be less concern that the additional oil-derived CO_2 emissions arising from EOR should be discounted from the CO_2 storage value of EOR.

4.4 CONCLUSIONS

This section presented a broad overview of the potential of CO_2 reuse technologies to accelerate the development and deployment of CCS and provided the following insights:

- Strong carbon pricing or equivalent regulatory mechanisms will ultimately be necessary to drive widespread commercial deployment of CCS. However, where demonstration projects do proceed, reuse revenues can act as a moderate offset to CCS costs and help to accelerate the demonstration phase which is an essential pre-cursor to the later commercial deployment phase of development.
- Based on current and forecast markets, the potential CO_2 reuse demand is too small for it to make a material contribution to global CO_2 abatement, and it does not provide a material alternative to conventional geological storage at the scale required. The value of reuse as a means of accelerating the demonstration and commercial deployment of CCS centres on the supplementary revenue that mature reuse technologies, particularly EOR, provide to demonstration project development in the absence of strong carbon prices.
- Mature CO_2 reuse technologies such as EOR can play a useful role in supporting early CCS demonstration, but as the surplus of available CO_2 grows and as the longer term bulk CO_2 market price weakens, the scope for EOR and the longer-term permanent storage technologies will depend on recognition of their mitigation credentials and their cost competitiveness relative to alternative mitigation options.
- In a strong carbon price environment there is limited potential for reuse technologies where CO_2 storage is temporary – except in circumstances where regulators accept that the process either replaces natural reservoir CO_2 or the product replaces products derived from fossil fuel.

PART 3
KEY FINDINGS, RECOMMENDATIONS AND CONCLUSIONS

1. KEY FINDINGS

Mature reuse technologies, especially EOR, can provide a revenue supplement to the economic viability of early CCS demonstration projects which are necessary to pave the way for later-stage widespread CCS deployment. The early demonstration projects, are required to optimise costs through 'learning by doing' as well as to gain community confidence in CCS and to establish enabling legislative and regulatory regimes. While EOR has a role to play in accelerating the near term development of initial demonstration projects in favourable locations, it is less evident that reuse can provide sufficient demand for CO_2 to materially facilitate later-stage widespread CCS deployment.

More particularly, the key findings include:

1. The current and potential future demand for CO_2 reuse is only a few per cent of anthropogenic CO_2 emissions, and while reuse does not have material global CO_2 abatement potential it has the potential to provide a moderate revenue stream for near-term CCS project development in favourable locations where reuse applications and markets are close to the emission source.
2. EOR will remain the dominant form of CO_2 reuse in the short to medium term due to its maturity and large scale utilisation of CO_2. As a result it has a role to play in supporting the near-term development of large scale CCS demonstration projects in regions of EOR potential and in the absence of strong carbon pricing. This initial phase of large scale CCS demonstration is an essential pre-requisite to commercial deployment, and is critical to the establishment of practical legal and regulatory regimes, to community acceptance and to CCS project optimisation and cost reduction.
3. Most of the emerging reuse technologies still have years of development ahead before they reach the technical maturity required for deployment at commercial scale. Mineralisation technologies may ultimately provide a complementary form of CCS to geological storage, and can facilitate abatement of a small proportion of anthropogenic CO_2 emissions. Technologies that reuse CO_2 in fuel production may also provide indirect mitigation through replacement of fossil fuels. While these are useful attributes, due to their lengthy development timeframes they cannot provide a driver to accelerate the commercial deployment of CCS.
4. CO_2 reuse has the potential to be a key component of large-scale CCS demonstration projects in emerging and developing economies, where there is strong demand for energy and construction materials and less likelihood of the early adoption of carbon pricing. The main focus will be on EOR due to its maturity, and potential CO_2 utilisation capacity, however carbonate mineralisation, CO_2 concrete curing, bauxite residue carbonation, enhanced coal bed methane (ECBM), urea yield boosting and renewable methanol may also be of interest in emerging economies such as China and India. However, as noted in point 3 above, some of these technologies are still in the early stages of development and may not be at the required maturity for deployment at commercial scale to coincide with CCS development timeframes.
5. The current market price (US$15–19/t) for bulk CO_2 is indicative of the upper limit of prices that can be expected in the future. There is little prospect of a general long-term strengthening of the current bulk CO_2 market price for reuse, and there is every prospect of downward pressure on prices as and when restrictions on CO_2 emissions are introduced. The revenue generated from reuse will be inadequate to drive the development of CCS for power, steel and cement plants, all of which will require a strong carbon price and/or project-specific funding. CO_2 supply from low-cost sources, such as natural gas processing and fertiliser production, is likely to dominate reuse supply growth into the medium term.

6. CO_2 reuse has an initial role to play in supporting the demonstration phase of CCS development in the absence of strong carbon prices and in emerging economies. However that initial role, centred on EOR, becomes less important as and when the cost of emitting carbon rises, which must ultimately happen to facilitate the widespread commercial deployment of CCS. Furthermore, as noted in point five above, the likelihood is that the market price for bulk CO_2 will fall as carbon prices rise with tightening restrictions on emissions.

1.1 REUSE AS AN ECONOMIC DRIVER

In order to accelerate CCS in the later widespread deployment stage, the reuse technologies must not only demand large quantities of CO_2 and generate a revenue stream, but should also be close to commercial operation in order to be aligned with the CCS development timeframe. Furthermore, the magnitude of impact a given technology can have in accelerating the widespread uptake of CCS is also largely a question of economics of the bulk CO_2 market, end product value and drivers such as the implementation of a carbon price.

An evaluation of the economics and commercial frameworks associated with the reuse of CO_2 formed an integral part of this report (part 2) and highlighted the following key findings:

1. In the near term, revenue from CO_2 reuse will not be a primary driver for CCS deployment. However, where demonstration projects do proceed, reuse revenues can act as a moderate offset to CCS costs, and hence will benefit early demonstration projects rather than projects in the longer term phase of wide-spread commercial deployment. That is because the potential long-term revenue generated by emitters in supplying CO_2 to reuse technologies is likely to experience downward pressure due to the large long-term CO_2 supply surplus. Introduction of a carbon price will depress the current bulk CO_2 market price due to increased need for emitters to dispose of their CO_2 to avoid paying the carbon penalty.
2. Widespread commercial deployment of CCS will require a global carbon price much larger than the prospective bulk CO_2 market price for selling CO_2 for reuse. Revenue generated from CO_2 reuse, mainly from EOR, is likely to provide moderate economic support to early demonstration projects, but in the longer term the introduction of a carbon price will be the critical driver for the widespread uptake of CCS across the full range of stationary CO_2 sources. The current estimated cost gap for CCS from power, steel and cement plants is several times larger than the current bulk CO_2 market price, and downward pressure on this market price is likely to eventuate as and when carbon prices increase. For industrial sources where capture costs are low, a modest initial carbon price may be enough to trigger the further near-term deployment of CCS beyond the current population of gas-related CCS projects.
3. Uncertainty in regulatory acceptance of CO_2 reuse mitigation credentials presents challenges for the uptake of reuse technologies. Investments in CO_2 reuse technologies that do not provide permanent storage of CO_2 are ultimately exposed to greater risks due to the uncertainty of the carbon penalty liability between the emitter and the end product. At one end of the spectrum, the CO_2 emitter (power station or industrial source) may bear the full carbon price/tax despite passing on the CO_2 for reuse. This will make capture for the purpose of reuse commercially unattractive. At the other end of the spectrum, if the carbon price is passed on to the end product then there is exposure to risk that the product may not be as commercially competitive.

1.2 REUSE AS A DRIVER OF LEARNING AND ACCEPTANCE

Mature forms of reuse have the potential to advance the development of the earlier phase of initial large-scale demonstration projects, particularly in the absence of strong carbon pricing. These demonstration projects play a critical role in the development of practical regulatory regimes in gaining community acceptance of CCS and in project and cost optimisation through learning by doing.

The key findings of this report's analysis of the impact of reuse technologies on initial CCS demonstration development are as follow:

1. CO_2 reuse for EOR combined with measuring, monitoring and verification (MMV) can provide learnings associated with storage and can help foster community acceptance of storage. The use of CO_2 in EOR, when combined with MMV to track migration of the CO_2 plume, illuminates the geological detail of the storage reservoir and enhances understanding of the factors influencing sub-surface CO_2 migration. The Weyburn-Midale and Cranfield projects are examples of this potential.
2. CO_2 reuse for EOR, and to a lesser extent other reuse technologies, may also provide opportunities for capture development and learning. While low-cost CO_2 sources of concentrated CO_2 (such as natural gas processing fertiliser plants) will generally provide the most competitive supply for reuse, there will also be circumstances where revenue from reuse and public funding are combined to develop demonstration projects based on capturing CO_2 from power, steel and cement plants. Such demonstration projects will provide additional or earlier opportunities for capture learning. Non-EOR reuse applications may also enable capture projects to proceed in locations where viable geological storage is not immediately accessible.
3. CO_2 reuse is likely to be a key component of CCS demonstration projects in emerging and developing economies, where there is strong demand for energy and construction materials and less likelihood of the early adoption of carbon pricing. EOR will be the key interest, but carbonate mineralisation, CO_2 concrete curing, bauxite residue carbonation, ECBM, urea yield boosting and renewable methanol, may be of particular interest to emerging economies.

1.3 RECOMMENDATIONS

Recommendations for priority action are:

1. Map regional opportunities for CO_2 reuse projects, identifying the point sources of CO_2, especially concentrated sources, align with strong demand for products derived from CO_2. By necessity the evaluation of technologies and commercial aspects in this report was undertaken at a global level. Local project opportunities may present themselves when targeting specific regions, where strong demand for CO_2-derived products aligns with point sources of CO_2. The identification of low-cost high concentration CO_2 sources, such as those associated with gas processing, coal gasification and fertiliser production, will be particularly important in identifying viable opportunities, particularly in emerging economies.

2. Encourage the deployment of CO_2-EOR outside of North America and maximise its associated learning and community acceptance opportunities. The present study has identified CO_2-EOR as the CO_2 reuse technology best placed to accelerate conventional CCS and is likely to be important in facilitating early demonstration projects. The CO_2-EOR industry in North America is mature, but deployment outside of North America has been limited to date. The adoption of rigorous measuring, monitoring and verification (MMV) of the subsurface CO_2 plumes generated by EOR is the key to maximising the storage learning and community acceptance benefits they can provide.
3. Make CO_2 reuse opportunities more the focus in programs that facilitate the development of large-scale CCS demonstration projects in emerging and developing economies. The mapping and ranking of point source CO_2 emissions and reuse opportunity alignments should provide a valuable tool in prioritising support and/or funding to facilitate the development of large-scale CCS demonstration projects in developing and emerging economies.

2. CONCLUSIONS

CCS is a key technology in the quest to reduce global CO_2 emissions. It has a major role to play in the reduction of emissions from fossil fuel use in power generation, and is the only evident option for materially mitigating the CO_2 emissions from a range of major industrial processes including steel and cement making, gas processing and fertiliser production.

CCS is currently deployed at industrial-scale only in the oil and gas industry where it is used to mitigate CO_2 emissions from gas processing and in EOR. Because of its wider significance as a mitigation technology, governments and organisations around the world are striving to accelerate and extend the development and deployment of CCS. As an early response to one of the priority actions in the CCUS Technology Action Plan, this report has evaluated the potential of CO_2 reuse technologies as a means of accelerating the uptake of CCS.

A detailed investigation has shown that CO_2 reuse technologies are unlikely to have a significant direct impact in the global challenge to reduce emissions, in line with the findings of the 2005 IPCC Special Report on CCS. However, mature reuse technologies that require a concentrated stream of CO_2 and provide permanent storage of CO_2, such as EOR (with MMV programs in place) can provide a revenue supplement to the economic viability of early CCS demonstration projects, which are necessary to pave the way for later-stage widespread CCS deployment. The early demonstration projects are required to optimise costs through "learning by doing" as well as to gain community confidence in CCS and to establish enabling legislative and regulatory regimes. While EOR has a role to play in accelerating the near-term development of initial demonstration projects in favourable locations, it is less evident that reuse can provide sufficient demand for CO_2 to materially facilitate later-stage widespread CCS deployment.

Regardless of the degree of permanence of storage, CO_2 reuse technologies that require a concentrated stream of CO_2 (from conventional capture plants) provide opportunities for capability building, knowledge sharing, and learning, with a subsequent impact on capture plant cost reduction. EOR is the candidate technology in this regard due to its maturity and scale.

Some reuse technologies can utilise a dilute CO_2 stream directly, e.g. flue gas from power generation. Where these technologies also provide permanent storage, they may have potential to offer a low-cost form of 'alternative CCS'. Consequently they have potential to act as a transitional measure to conventional CCS (e.g. if there are delays in developing integrated CCS projects). Unfortunately, these technologies will not contribute to capability building or cost reductions for conventional capture plants.

Other than CO_2-EOR, there are limited CO_2 reuse technologies that are of sufficient maturity and scale to accelerate the uptake of CCS. However, if a particular technology were to arise that has potential for large-scale CO_2 reuse, it will generally require funding and/or policy support from governments, and would need an ambitious development pathway to be aligned with the CCS deployment timeframe.

APPENDICES

APPENDIX A: CO_2 FOR USE IN ENHANCED OIL RECOVERY (EOR)

OVERVIEW

Enhanced oil recovery (EOR) involves flooding oil reservoirs with injected CO_2 to displace oil contained within. At the start of a well's lifecycle, oil will flow freely via the pressure gradient, known as primary production. This kind of production recovers 5 per cent to 40 per cent of the oil originally in place.

Over the life of the well, the pressure underground will become insufficient to force oil to the surface, meaning secondary and tertiary recovery methods need to be employed – if economically viable to continue with oil extraction. Various agents have been used for EOR, among them CO_2, increasing original oil recovery by 7 per cent to 23 per cent further from primary extraction.

Oil displacement by CO_2 injection relies on the behaviour between CO_2 and crude. This interaction depends on the oil's weight, and the reservoir characteristics. In high pressure applications with lighter oils, CO_2 is miscible with the oil (in all proportions forms a single phase liquid), with resultant swelling of the oil, and reduction in viscosity, and possibly also with a reduction in the surface tension with the reservoir rock. All these effects serve to improve the flow of oil to the production wells.

In the case of low pressure reservoirs or heavy oils, CO_2 (potentially along with alternating water injection) will form an immiscible fluid, or will only partially mix with the oil. Some oil swelling may occur, and oil viscosity can still be significantly reduced. However, in immiscible CO_2 flooding the main function of the CO_2 is to raise and maintain reservoir pressure. CO_2 immiscible flooding is considered where the reservoir permeability is too low for water flooding, or where the geochemistry or other geological conditions are unfavourable for water flooding.

During these CO_2-EOR applications, more than 50 per cent and up to 67 per cent of injected CO_2 will return to the surface with the extracted oil, requiring separation and reinjection into the well to prevent release into the atmosphere and to reduce operating cost of obtaining additional CO_2.

The effectiveness of CO_2-EOR is dictated by reservoir characteristics, such as temperature, pressure, height, angle and permeability. For example, injection depth must be generally greater than 600m and well pressure over 10MPa into light weight oil to achieve the desirable miscible flood, described above. These factors along with the well's stage of production must be considered when selecting a reservoir for CO_2-EOR.

TECHNOLOGY STATUS

CO_2 for EOR is a proven technology, first applied in the early 1970s in Texas, USA and has since been developed constantly and applied in many parts of the world. Due to this, EOR with CO_2 can be considered commercial.

Companies employing this technology for capture on industrial plants (e.g. syngas, natural gas sweetening, coal power, fertiliser, or cement production) and within transport range of suitable oil wells, with existing demonstration size or greater EOR projects, include:

Andarko Petroleum Corporation (Salt Creek, USA), Chevron (Rangely-Webber EOR, USA), the Chinese Government (Daqing EOR, China), EnCana (Weyburn, Canada), and Penn West Energy Trust (Pembina Cardium EOR, USA).

RESEARCH STATUS

Research concerning this technology in the past suggested that CO_2 flooding was only viable in certain types of reservoirs, which in the case of the US, referred to the Permian Basin found in Texas and New Mexico. New research determined the successful implementation of CO_2 in any kind of reservoir as long as a reasonable minimum miscibility pressure (MMP) was achieved. Tests on nearly every kind of rock showed CO_2's reliability in EOR, which could be implemented in many more areas which were previously considered as not suitable for this practice.

The U.S Department of Energy is investing and supporting research to aid America's oil producers to expand their CO_2-EOR operations and implementations, as an alternative to water use. Currently, the research has made CO_2 flooding the fastest growing EOR technique in the U.S, whilst other techniques have been steadily declining in comparison.

PROJECT DEVELOPMENT

Developments for EOR have been taking place all over the globe. In North America, the Department of Energy (DOE) estimated around 50 Mt CO_2/yr being currently used for CO_2-EOR. Of this, 75 per cent is applied in projects in West Texas alone.

Projects employing industrial CO_2 capture and transport to an injection site include, Salt Creek, USA and Weyburn, Canada, which inject approximately 4000–6000 tCO_2 per day with total planned storage of 20Mt for each project. Incentives proposed by the National Energy Technology Laboratory (USA) into projects for CO_2-EOR estimate that these technologies could double in implementation from 2010–2020.

Growth could be much greater in other countries considering the USA has only 1.6 per cent of the world's proven oil reserves. As oil production declines from existing wells in the Gulf States, CO_2 use for EOR, if economic, would be many times greater than the USA's current annual application based on proven oil reserves.

CO_2 UTILISATION AND RESOURCE QUANTITIES

Commercial scale of CO_2-EOR injection differs according to their locality and proximity to CO_2 producing sources. In the case of West Texas, for example, CO_2 comes from naturally occurring reservoirs.

CO_2 injection per oil displacement rate is very dependent on reservoir characteristic (e.g. size, pressure, temperature). This varies dramatically and would need to be examined on a site by site basis. Projects employing industrial CO_2 capture and transport to an injection site include, Salt Creek, USA and Weyburn, Canada, which inject approximately 4000–6000 tCO_2 day with total planned storage of 20Mt for each project.

POTENTIAL MARKETS

CO_2-EOR is very specific to the location. CO_2 sources and transport options local to a suitable reservoir determine if EOR is a cost effective way to extend well production life.

CO_2-EOR with CCS capture from industrial applications is on the cusp of being a commercial level of deployment based on the size of the projects currently active, such as Salt Creek, USA and Weyburn, Canada. Offshore CO_2-EOR is yet to be demonstrated.

SIZE OF MARKET

In North America where CO_2-EOR is most widely employed, the Department of Energy (DOE) estimated around 50 Mt CO_2/yr is currently used.

Currently, CO_2-EOR is used to produce about 250,000 barrels per day of oil in the US that are incremental to base case production. A recent study by Advanced Resources International states that an additional 4 to 47 billion barrels of domestic resources could be economically recovered using CO_2-EOR. The study notes that at least 8 billion tonnes of CO_2 could be sequestered in the US by using EOR[6].

MARKET DRIVERS

Apart from the obvious benefits of increased oil production and GHG reduction through CO_2 storage (commercial benefit if/ when Environmental Trading Schemes (ETS) are in place), other commercial benefits are provided through limiting a government's reliance on foreign oil and increased tax revenue. Jobs will also be created and maintained through prolonging reservoir life and the CCS chain (on an industrial plant) providing CO_2 for EOR. However, the main market driver for use of EOR will be the prevailing and forecast future oil prices.

LEVEL OF INVESTMENT REQUIRED (TO ADVANCE THE TECHNOLOGY)

A large amount of investment is required in order to advance and further commercialise the technology. The CENS project model, which is looking at the feasibility of using CO_2-EOR technology in the North Sea, shows investment costs of roughly:

- US$1.7 billion for CO_2 pipeline.
- US$2.2 billion for CO_2 capture plants.
- US$5.0 billion for EOR investment in oilfields (Sharman 2004).

These of course are project investment costs, as opposed to research costs. Future project economics may one day come to make such an investment into North Sea EOR a possibility.

POTENTIAL FOR REVENUE GENERATION

Through aggressive greenhouse gas (GHG) reduction targets, Western governments are supporting the development of CCS by funding demonstration projects, with the aim to see CO_2 capture and storage from industrial applications become economically and technically viable for widespread deployment. CO_2-EOR is a stepping stone in this process in which revenue can be generated to help support the cost of CCS implementation and operation.

6 World Resources Institute: CO_2-Enhanced Oil Recovery http://www.wri.org/publication/content/8355

A decline in the world's established oil production means CO_2-EOR could be employed more widely in the future to maintain oil production. For example, Oman's oil production between 2001 and 2007 fell by 27 per cent, but by 2009, due largely to EOR projects, oil production increased by 17 per cent. Additional oil revenue benefits both governments and the production companies, which could lead to future funding of CO_2-EOR.

PRICE SENSITIVITY

A rise in oil price would make the additional cost of CO_2-EOR more appealing; however the current fluctuating oil price makes future investment decisions difficult.

The high CAPEX and OPEX of CCS from industrial applications potentially erode the revenue benefits of increased oil production through EOR.

Research, including the CENS project in the North Sea suggests that the break-even oil price is around US$30/bbl assuming CO_2 capture costs of US$48 per tonne ($CO_2$ Norway, 2005). As at June 2010 crude oil was trading at US$77/bbl.

COMMERCIAL BENEFIT

This will develop when oil becomes scarce and the increased cost can support CO_2-EOR from industrial sources. This could be in parallel to CCS technology improving to be more efficient (reduced OPEX) and more cost effective (reduced CAPEX) to install/ retrofit to existing plants.

BENEFITS

Increased oil revenue through CO_2 storage would be very substantial all over the world. In the US alone in 2005, it was estimated that CO_2-EOR could increase oil production up to 2–3 million barrels per day by 2025. This would in turn reduce the countries trade deficit of over US$1.7 trillion through reduced oil imports and could provide 500,000 well paid domestic jobs from the direct and indirect benefits of this increase in oil production. Return on investment of this kind, through oil production, could assist industrial CCS roll-out in the short term.

CO_2-EOR could present a cheaper option for EOR developers. It is also estimated, that in order to encourage the use of CO_2 from power plants, fiscal incentives such as tax or emission trading credits will be issued. This would enable the expansion of the CO_2-EOR industry and facilitate the technology to grow in more areas where power plants are present – which are abundant especially in developed countries.

BARRIERS

High CAPEX and OPEX for CCS implementation, along with uncertainty over the long term oil price and oil well production timelines when secondary production is optimal have kept oil companies from using EOR. Added to this, unclear regulations and wavering public support (particularly for onshore injection) of CO_2 have provided barriers to EOR.

The cost of CO_2-EOR with industrial capture will provide a barrier to developing countries, while offshore CO_2-EOR had not been implemented in any county due to the high cost involved, despite CO_2-EOR itself being very applicable if the country is an oil producer and wants to maintain its future oil production.

APPENDIX B:
CO_2 AS A FEEDSTOCK FOR UREA YIELD BOOSTING

OVERVIEW

The global agricultural industry is highly dependant on the supply of inorganic, fossil derived fertilisers to ensure adequate crop yields. Food shortages already exist globally but without the addition of fertilisers to agricultural land current monocrop plantations would not be able to meet the demand of today's world food market.

The three main constituents of inorganic fertiliser are nitrogen (N), phosphorus (P) and potassium (K), commonly marketed as NPK fertilisers and including smaller amounts of other nutrients.

Urea is one of the most common forms of solid nitrogen fertiliser. Urea is produced by the reaction between ammonia and CO_2. This is a two step process where the ammonia and carbon dioxide react to form ammonium carbamate which is then dehydrated to urea. The final product is a prilled or granulated solid which once applied to agricultural land reacts with water to release the CO_2 and ammonia. The CO_2 returns to atmosphere and the ammonia decomposes further to supply nitrogen at the correct rate to the crops.

Urea can also be used to produce urea-ammonium nitrate (UAN) one of the most common forms of liquid fertiliser.

Urea is a feedstock to a range of other industries, including the chemical industry, and around 10 per cent of urea produced globally will be processed to products such as animal feed, formaldehyde resins, melamine, and adhesives.

TECHNOLOGY STATUS

Urea has been produced on an industrial scale for over 40 years. CO_2 capture plants for urea yield boosting have been installed since late 1990's. The technology is relatively mature.

Urea production is carried out on a very large industrial scale. The size of plant is constrained only by the size of the upstream ammonia facility. A typical plant may produce 1,500 tonnes of urea per day, with systems up to 5,000 tonnes per day considered feasible. However, surplus ammonia from natural-gas based plants may be in the range 5 per cent–10 per cent. Consequently, capture plants installed for this purpose will continue to be <1000tpd in size. Coal-based urea production facilities produce surplus CO_2 and are a source of rather than a sink for captured CO_2.

RESEARCH STATUS

Research into urea production is focussed on enhancing the efficiency of the process to improve conversion rates, to reduce energy consumption, to reduce atmospheric emissions of ammonia and to reduce waste by-products in order to reduce production costs.

CO_2 UTILISATION

The production of urea consumes CO_2 at the rate of 0.735–0.75 tonnes of CO_2 for every tonne of urea produced.

The CO_2 source for urea yield boosting is typically from capture plant installed on site to capture CO_2 from the reformer flue gas. Urea production is inherently linked to ammonia production. Urea plants are generally located adjacent to or in proximity to an ammonia plant and close to major sources of natural gas.

In 2009 154.9 Mt of urea was produced globally. This equates to approximately 116.2Mt of CO_2 feedstock used. However, this is generally captive CO_2. The component of non-captive CO_2 is relatively small.

Once applied to the land and contacted with water the reaction used to form urea is reversed, the ammonia produced is absorbed by the plants and the resultant CO_2 is released to atmosphere, meaning CO_2 is not sequestered. The permanence of storage for CO_2 contained in urea which is further processed for example in the chemical industry is dependent on the process and the nature of the final product, this however accounts for a small amount of urea use.

POTENTIAL MARKETS

Market analysts estimate that 187 million tonnes of urea fertiliser consumption is expected by the end of 2013–14. Much of the growth is expected to take place in South Asia and East Asia, where demand will propel more than 60 per cent of the world's fertiliser growth.[7]

SIZE OF MARKET

According to the International Fertiliser Association the current market for urea is 159.4Mtpa (equivalent to approximately 119.6Mtpa CO_2).

MARKET DRIVERS

The commercial and economic feasibility of the technology is likely to be affected by the relative prices and demand of ammonia and urea. For example, if the demand (and price) of urea is strong relative to ammonia then there is likely to be an incentive to convert the surplus ammonia to urea using recovered CO_2 through this technology. At present global ammonia is trading at prices in the region of US$350-US$425/tonne and urea at US$205-US$285/tonne. However, the volatility in the price and demand of each of these markets will impact the long term feasibility of implementing this technology

LEVEL OF INVESTMENT REQUIRED (TO ADVANCE THE TECHNOLOGY)

As an already commercial technology, additional investment to advance the technology is not a necessity. However, R&D is likely to continue based solely on commercial drivers, with the aim of decreasing CO_2 capture plant capital and operational costs.

7 Fertilizer Demand Most Likely To Bounce Back in 2010 (September 2009) http://www.glgroup.com/News/Fertilizer-Demand-Most-Likely-To-Bounce-Back-in–2010-43308.html

POTENTIAL FOR REVENUE GENERATION

The revenue potential will be dependent on the relative market prices of urea and ammonia, and the costs associated with the CO_2 capture technology.

PRICE SENSITIVITY

As noted above, viability and the magnitude of revenue will be sensitive to the relative prices and demand of both urea and ammonia.

COMMERCIAL BENEFIT

The commercial benefit of the technology is likely to be limited by the comparative costs of producing urea using this technology over traditional methods.

BENEFITS

Urea yield boosting represents a currently commercial application of CO_2 capture technology.

BARRIERS

The main barriers associated with the deployment of urea yield boosting technology include:

- Volatility in the relative price and demand for urea and ammonia making long term appraisal difficult.
- The potential high capital costs of CO_2 capture infrastructure.

APPENDIX C: CO_2 AS A WORKING FLUID FOR ENHANCED GEOTHERMAL SYSTEMS (EGS)

ENHANCED GEOTHERMAL SYSTEMS (EGS)

OVERVIEW

Enhanced geothermal systems (EGS) formerly known as hot fractured rocks (HFR) or hot dry rocks (HDR) are a new type of geothermal technology whereby underground reservoirs which are not naturally suitable for geothermal energy extraction can be made so through economically viable engineering procedures. The requirement for significant engineering work prior to heat extraction distinguishes EGS from conventional geothermal applications (Gurgenci, 2008).

In standard EGS, water or brine is circulated in a continuous loop through the reservoir, located three kilometres or more below the Earth's surface where heat is generated by special high heat producing granites. The circulating fluid extracts heat from the granite raises it to the surface where it is transferred to a secondary fluid (typically isopentane) through to a turbine generator to generate electricity.

A new approach to this concept is currently being pursued whereby supercritical CO_2 is circulated as the heat exchange fluid (or working fluid) instead of water or brine to recover the geothermal heat from the reservoir and either (a) transfer heat to a power cycle fluid or (b) generate power directly through a supercritical CO_2 turbine before being sent back to the reservoir. Supercritical CO_2 holds certain thermodynamic advantages over water in EGS applications and would achieve geologic storage of CO_2 as an ancillary benefit. This new concept is expected to significantly increase the cycle efficiency and have a favourable effect on the financial viability of an EGS project (Gurgenci, 2008).

The process will leave significant volumes of CO_2 sequestered underground, (geological storage). However, long term permanence (leakage) and MMV will be key issues.

TECHNOLOGY STATUS

Commercial production of geothermal energy is currently limited to hydrothermal systems. EGS for power generation is still relatively novel technology and is not yet developed at a large scale. Attempts to develop the technology have all employed water as the heat transfer medium (considered as conventional EGS). Two systems are in operation in France and Germany generating 1.5 MW and 3 MW respectively. There are a number of conventional EGS projects being developed and tested in Europe, United States, Australia and Japan. Currently the largest project in the world is a proposed 25 MW demonstration plant in the Cooper Basin in Australia.

Utilisation of supercritical CO_2 as the heat transfer medium in EGS is not yet a proven technology and is currently in the early stages of research and development. Testing the use of supercritical CO_2 as the working fluid in geothermal systems is projected to commence in 2013.

RESEARCH STATUS

The fundamental CO_2 science and the deep crustal environment are not yet understood. A number of research projects to develop the use of CO_2 as an EGS working fluid are underway. Two projects funded by the US Department of Energy (DOE) include:

- Symmyx Technologies, California – currently studying the chemical interactions between geothermal rocks, supercritical carbon dioxide and water.
- Argonne National Laboratory – studying the structural changes resulting from chemical interactions of supercritical CO_2 and water binary fluids with rocks under environments directly relevant to EGS.

In 2008 the Queensland Government awarded the Centre for Geothermal Energy Excellence at the University of Queensland AU$15 million for EGS research (over five years), a large portion of which will be used to develop CO_2 EGS technologies.

PROJECT DEVELOPMENT

Currently there are two developers seeking financing for field demonstration of supercritical CO_2 based EGS:

1. GreenFire Energy and Enhanced Oil Resources Joint Venture plan to build a 2MW CO_2 based EGS demonstration plant near the Arizona-New Mexico border. The drilling of wells to access hot rock is proposed to commence in 2010. The proposed location is projected to yield enough heat to generate 800 MW of power with potential to absorb much of the CO_2 generated by six large coal-fired plants in the region.
2. Geodynamics Ltd is one of about 16 companies active in geothermal power generation in Australia (and are the most advanced). Geodynamics Limited Innamincka 'Deeps' Joint Venture with Origin Energy are constructing a 1 MW EGS power plant at Habanero. Electricity generation is expected to occur by early 2012 following the successful completion of Habanero 4 and Habanero 5 (reservoirs), which will be the first Enhanced Geothermal Systems in Australia. Testing of use of supercritical CO_2 as the working fluid in the EGS is projected to commence in 2013.

   In November 2009, Geodynamics was successful in securing AU$90 million in funding under the Federal Government's Renewable Energy Demonstration Program to facilitate the delivery of the 25MW commercial-size demonstration plant. Geodynamics is due to make final investment decision on proposed $300 million, 25MW geothermal demonstration plant in the Cooper Basin by early 2013, after 12 months of successful operation of the Habanero closed loop. (This is two years later than previously stated). Geodynamics is targeting production of more than 500 MW by 2018, with capacity extending to 10,000 MW – the equivalent of 10 to 15 coal-fired power stations.

CO_2 UTILISATION

Based on long term reservoir pressurisation/fluid loss studies, fluid losses during circulation may amount to approximately 5 per cent of injection (Duchane, 1993). These figures suggest that there is potential capability to continuously sequester CO_2 by diffusion into the rock mass surrounding the reservoir.

Studies have indicated potential for geological storage of 24 tonne per day of CO_2 per MWe of EGS (1tonne/s of CO_2 per 1000MWe of EGS). This is equivalent to achieving geologic storage of the CO_2 emitted from 3,000MWe of coal-fired power generation.

Although the above estimate is reported as being very rough, it suggests a very large potential for CO_2 reuse and storage using EGS. Geodynamics target production of more than 500 MW by 2018 would potentially sequester 4.4Mt/y.

FUNDING/SUPPORT

The U.S. Department of Energy recently awarded US$338 million in federal stimulus funds for research in geothermal energy.

POTENTIAL MARKETS

EGS/HDR technologies using supercritical CO_2 are expected to be a cost effective way to use CO_2 from existing coal-fired power stations to generate new base load power, 24 hours per day.

SIZE OF MARKET

Australia is estimated to have 22000 EJ or 5000 times it annual energy consumption stored in EGS resources (K L Burns, 2000).

According to an estimate by Electricity Suppliers Association of Australia, EGS may provide up to 5 GW or 10 per cent of present Australian electricity generation 2030.

According to an MIT report the estimated US EGS resource base is more than 13 million EJ with an estimated extractable portion of over 200,000 EJ.

There is no detailed information available on the EGS potential of Europe or in developing countries.

MARKET DRIVERS

The long term forecast price of EGS electricity would make it competitive in a most carbon constrained electricity markets around the world.

LEVEL OF INVESTMENT REQUIRED (TO ADVANCE THE TECHNOLOGY)

A report by the Massachusetts Institute of Technology states that with a modest R&D investment of $1 billion over 15 years (or the cost of one coal power plant), it is estimated that 100 GWe or more could be installed by 2050 in the United States (Kubik (ed.) et al 2006)

POTENTIAL FOR REVENUE GENERATION

The revenue generation of EGS using CO_2 as a transmission fluid will be dependent on a number of factors and will largely be affected by the individual locations and quality of the individual sites. The main drivers affecting the profit potential include:

- the geothermal potential of the site (e.g. how much heat can be extracted through EGS);
- the prevailing price and demand of other sources of energy (e.g. natural gas and crude oil);

- the locality of a suitable CO_2 source (e.g. co-location of a CO_2 source will reduce costs associated with CO_2 capture, transport and storage); and
- whether a carbon trading scheme is in place.

PRICE SENSITIVITY

The price of the technology will be affected by a number of factors including:

- the prevailing price and demand of other sources of energy (e.g. natural gas and crude oil);
- the forecast future energy demand; and
- carbon price (if applicable in location).

COMMERCIAL BENEFIT

The main commercial benefit of the technology is the potential to tap into the energy market to meet the high forecast growth in energy demands. This is further emphasised by the pledges and targets made by over 60 of the world's major governments to increase the use of energy from renewable sources. The particular use of CO_2 rather than water in this technology also has a number of commercial benefits such as the advantages of CO_2 as a working fluid over water and the availability of CO_2 sources globally.

BENEFITS

There are a number of benefits associated with the use of supercritical CO_2 instead of water for EGS. These include:

- CO_2 storage-potential to sequester 1 tonne per second of CO_2 for each GW of electricity generated (site specific);
- minimised water usage;
- favourable thermodynamic properties resulting in much larger flow rates, reduction in circulating pumping power requirements, increased efficiency and greater power output;
- minimised losses during heat transfer due to (potential) elimination of binary cooling;
- reduction or elimination of scaling problems (such as silica dissolution and precipitation in water based systems);
- HDR reservoirs with temperatures > 375ºC (the critical temperature for water) could be developed without problems associated with silica dissolution; and
- carbon credits gained from sequestering the CO_2 would offset some of the costs of drilling deep EGS wells.

The series of potential advantages that supercritical CO_2 offers may help to expedite commercial exploitation of some geothermal resources.

BARRIERS

Enhanced geothermal systems for power generation are still a relatively novel technology and being proven. There are a number of significant issues that need to be resolved for successful development of the technology. These include:

- the geochemistry of supercritical CO_2;
- dealing with reservoir water;
- long term effects in terms of reservoir connectivity;
- the source of CO_2;
- the long term retention of CO_2, including seismic triggers and events resulting in CO_2 leakage to the surfaces;
- the lifetime of HDR geothermal systems may be difficult to prove; and
- the design and optimisation of turbines and air-cooled heat exchanger systems to operate with supercritical CO_2.

Potential barriers to implementation include

- proximity of the CO_2 source and access to at an acceptable cost;
- proximity of the EGS to the electricity grid;
- long-term responsibility for the resultant reservoir, including the liability for future CO_2 leakage; and
- the Geothermal industry has expressed concern regarding:
  - the high cost of CCS which may threaten the long-term viability of the use of CO_2 for EGS.
  - the future availability of CO_2 if CCS is only a transitionary technology.

APPENDIX D: CO_2 AS A FEEDSTOCK FOR POLYMER PROCESSING

POLYMER PRODUCTION

OVERVIEW

Polymers are made up of large chains of repeating structural units, generally formed with a carbon backbone, and displaying a wide range of physical properties. Polymers can be created form natural sources (such as rubber) or synthetic sources.

Currently, the most widely used feedstock in polymer production is petroleum derived, such as ethylene or propylene which, once reacted, make-up chains in polyethylene (PE) or polypropylene (PP), respectively. PE and PP represent the largest volume of polymers currently produced. PE is used to produce a range of items including plastic bags, milk bottles and film wrap. PP creates and forms parts of item such as automotive components, textiles and polymer banknotes.

A new approach to polymer processing is to combine traditional feedstocks with CO_2 to synthesise polymers and high value chemicals. The technology transforms waste carbon dioxide into polycarbonates using a proprietary zinc based catalyst system, which reacts CO_2 and epoxide molecules. An epoxide is a three-membered ring molecule, such as ethylene oxide. Based on the type of epoxide used, the polymer will have different properties – hard, soft, transparent, or opaque. The zinc-based catalyst allows the CO_2 to react at low temperature and pressure in a very efficient manner, providing a low energy pathway for utilising CO_2 to manufacture plastics and chemicals.

The polymers created by this process are polypropylene carbonate (PPC) and polyethylene carbonate (PEC). Such polymers can contain up to 50 per cent carbon dioxide or carbon monoxide and therefore have a significantly reduced carbon and energy footprint compared to the materials they will replace. Therefore this technology creates a useful demand for CO_2 as a product, which waste CO_2 sources could supply, while reducing demand for finite oil based feedstocks.

TECHNOLOGY STATUS

The potential of CO_2 as a feedstock was discovered back in 1969[8], when CO_2 and epoxide were first copolymerised over a zinc catalyst by researchers. Having a widely available feedstock was a significant discovery, however the process was limited at the time by needing large amounts of energy to break the CO_2 bonds and form polymer chains.

Through the use of a new proprietary catalyst which is claimed to reduce the energy of polymerisation, production of CO_2 based plastic material is currently performed on a pilot scale by Novomer Ltd at Kodak Speciality Chemicals facility in Rochester, NY, and has been since December 2009. To date, Novomer have demonstrated the process in a 1,500 litre batch reactor and are investigating processing polymers using a continuous flow reactor to improve production cost.

8 http://www.polysource.co.th/news/news-detail.php?news_id=14&lang=th

Simultaneously, the polymers are being tested in a range of conversion processes that include thin film extrusion to blow moulded bottles. Materials produced are being offered to potential customers for testing. Testing has indicated Novomers plastics are comparable or superior to traditional petroleum based plastics.

In March 2010, Novomer partnered with Praxair to supply the required repurposed CO_2 and Kodak Specialty Chemicals, a unit of Eastman Kodak to support polymer process development and scale-up. At the end of the project, in addition to enabling commercial-scale manufacturing capabilities for sustainable materials with several contract manufacturers, it is expected that several products will be customer qualified requiring commercial scale production of PPC polymers on a global basis.

RESEARCH STATUS

Using CO_2 as a polymer feedstock is possible through the use of a zinc based catalyst system, which reacts CO_2 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.

PROJECT DEVELOPMENT

Novomer are currently operating a pilot scale plant and are developing the process towards commercialisation, by investigating production of the polymer through a continuous flow reactor to improve costs. The most economical location for a commercial facility with access to CO_2 feedstock is also being determined.

The polymer itself is being developed with specific focus on optimisation and testing which impurities can be tolerated in the CO_2 supply source, the type of potential conversion processes (e.g. blow moulding and thin film extrusion) and testing of properties by potential customers to determine future applications.

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

- Department of Energy US$2.6 million grant to demonstrate the innovative reuse of CO_2.
- New York State Energy Research & Development (NYSERDA) US$475,000 for two phases of work, included a feasibility study and commercialization activities for the coatings and packaging markets.
- National Science Foundation US$400,000 to develop a continuous flow manufacturing process to make CO_2-based polymers.

CO_2 UTILISATION

Based on Novomer figures from their proprietary catalyst, it is estimated their polymers contain up to 50 per cent CO_2 by mass. CO_2 will be generated from a point sources (e.g. syngas production, natural gas sweetening, coal power production), which will likely require an additional processing step to increase the degree of purification. Considering the global PP market alone in 2007 was 45.1 Mt (Novomer 2010), if PPC can compete with this market, CO_2 utilisation could be significant. Total market share would see 22.5 $MtCO_2$ used as feed stock annually.

As a finished product, PPC could have a very long life cycle depending on the application which it's designed, giving CO_2 potential permanence of storage.

Initial studies have also indicated that aliphatic (compounds in which carbon atoms are linked in open chains) polycarbonates can be recycled via hydrolysis reactions and in some cases biodegraded. Aliphatic polycarbonates in ideal compost conditions can degrade in six months[9]. CO_2 will be released back into the atmosphere in this case, making CO_2 storage non-permanent.

POTENTIAL MARKETS

Polymers created in part from CO_2 could replace traditional petroleum based plastics such as polypropylene, polyethylene, 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 CO_2. The surfactants improve the solubility of CO_2 increasing oil recovery and creating permanent storage for the CO_2 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

Barrier protection can be further increased using polyethylene carbonate (PEC), with barrier properties over 100 times (Novomer 2010) greater than petroleum-based plastics. Oxygen oxidises and promotes biological growth leading to food spoilage, so barrier layers are commonly added to packaging plastics, creating a potentially large market for this application.

SIZE OF MARKET

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 c.6 per cent until 2015.

9 http://www.technologyreview.com/business/19697/?a=f#

MARKET DRIVERS

The main driver for the wide scale commercialisation of the technology is the potential to enter the polymer market. Even a relatively small market share of around 10 per cent would result in approximately 12.5 Mt of polycarbonate polymers produced annually. Additionally the ability to store CO_2 on a semi-permanent basis will help drive the technology forward, particularly in regions where a carbon scheme exists.

LEVEL OF INVESTMENT REQUIRED (TO ADVANCE THE TECHNOLOGY)

There is currently no publicly available information regarding the costs and investment requirements for implementation of the technology.

POTENTIAL FOR REVENUE GENERATION

The potential revenue generation is high if, as Novomer claim, 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.

COMMERCIAL BENEFIT

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.

BENEFITS

There are a number of benefits associated with the use of CO_2 as polymer feedstock:

- The chemicals and materials contain up to 50 per cent carbon dioxide or carbon monoxide and are claimed to have a significantly reduced carbon and energy footprint compared to the materials they will replace.
- Traditional chemical industry infrastructure can be used to manufacture the plastic.
- Polymers are reported to have a broad range of material characteristics, from stiff solid plastics to viscous liquids, based on the molecular weight (or "size") of polymer chains.
- PPCs are reported to have suitable stiffness, impact resistance, and oxygen barrier properties that allow them to be used in food and other flexible and rigid consumer packaging applications where these properties are critical.
- The use of carbon dioxide and carbon monoxide as feedstock instead of the corn-based feedstock used by other biodegradable plastics, means that the production of plastic will not compete with food production.
- Traditional barrier protection polymers (e.g. ethylene vinyl alcohol (EVOH) and polyvinylidene chloride (PVDC)) contribute greenhouse gases through large energy demands in the manufacturing process. PEC has similar properties yet sequesters CO_2 and will in turn displace the CO_2 of manufacture if the original product is replaced.

BARRIERS

There are a number of significant issues that need to be resolved for successful development of the technology. These include:

- Technology is still at a relatively early stage – it has only been demonstrated at a small scale (using a batch reactor).
- Being aliphatic polycarbonates, degradation could occur in as short as 6 months under the right compost conditions. CO_2 will be released back into the atmosphere in this case making CO_2 storage non-permanent.
- CO_2 is a very stable molecule and takes significant energy to split and allow reaction. Therefore this process was traditionally expensive and would contribute significant green house gas emissions on a commercial scale of production through the energy demands (assuming fossil fuel generated power). Research into new catalysts like Novomer have performed could improve this by lowering the activation energy of reaction. This is important as the cost of production must be equivalent to traditional polymers if CO_2 constructed polymers are to compete commercially.
- The source of CO_2 and the purity required could mean additional polishing at the point of source is required, increasing cost.
- 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.

APPENDIX E: CO_2 FOR USE IN ALGAE CULTIVATION

OVERVIEW

An aquatic plant, microalgae are one of the most abundant and highly adapted forms of life on the planet. They form the foundations of food chains and play a vital role in absorbing carbon dioxide from the atmosphere. Many species produce a high proportion of natural lipid by weight and over millions of years have been systematically fossilised in large deposits, transforming into the fossil crude we extract and use today. There is currently significant interest in the potential of algae to produce vast quantities of oil (mostly with a view to liquid transport fuel substitutes) at a price that is competitive with crude oil.

Aquatic microalgae represent a highly productive source of biomass that can avoid many of the challenges associated with utilisation of terrestrial biomass and '1st generation' biofuel crops by using non-productive land area and non-potable water for cultivation. The injection of CO_2 is seen as an important factor which improves the economics of algal growth systems making it a potential volume user of concentrated CO_2 streams. As with CO_2 supplemented atmospheres in industrial greenhouses, bubbling CO_2 through algal cultivation systems can greatly increase productivity and yield (up to a saturation point).

To date, there have been no known successful attempts to commercialise high volume production of algae strains for energy and material purposes as the growth and processing variables are difficult to control at competitive cost. That said, many of the developments in recent years are shrouded in commercial secrecy and it represents potential for a CO_2 reuse option of significant scale, so the precise status is difficult to ascertain.

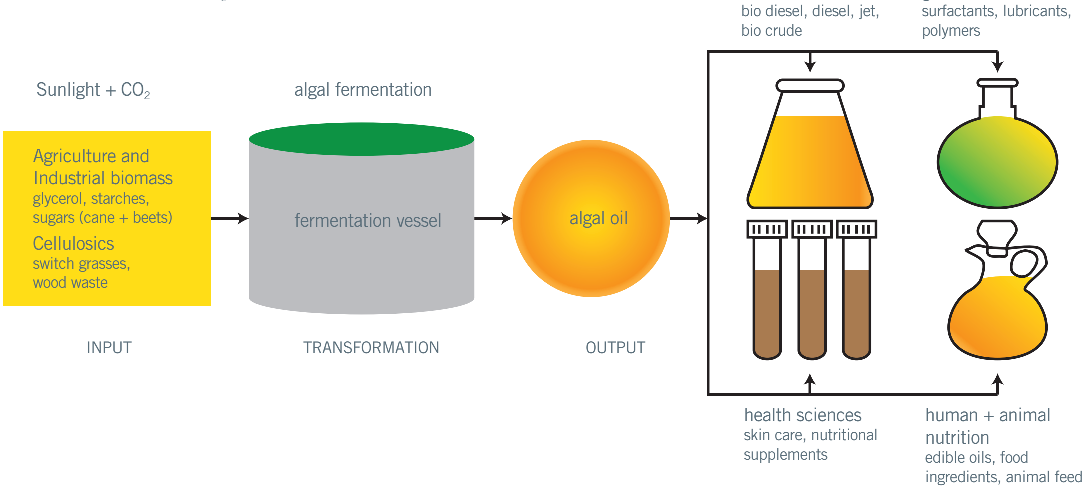
Algae can be cultivated in systems which are controlled to varying degrees. Generally these systems can be described as either 'closed' or 'open'. Closed systems or 'photo-bioreactors' (PBRs), typically banks of transparent tubes or bags through which CO_2 is pumped, offer the highest degree of control over environmental parameters and reduce the risk of bacterial contamination, though they are inherently capital intensive and complex. Open systems, consisting of a pond mixed by a large paddlewheel, are technologically simple and are relatively low cost. Both systems require a mixture of critical nutrients, water and sunlight.

Once harvested, algal biomass can be processed in numerous ways to extract economic value, depending on the desired output product/s. Commonly, the natural oil fraction (some species are capable of producing 70%wt oil content) is sought as a feedstock for biodiesel production, food products, chemicals, nutriceuticals or for cracking into smaller base units before reforming to a wide range of other products. Where CO_2 abatement/capture is the focus, high oil-yielding species are not preferred as this compromises productivity overall however the biomass product is still valuable. The biomass husk that remains after oil extraction has uses as fertiliser or animal feed. The algae biomass can also be fermented to produce ethanol, digested anaerobically to produce biogas or pyrolysed to generate oil, gas and char. There are also certain algae that secrete ethanol or even hydrogen as a by-product of metabolic processes and these are also under investigation.

The potential productivity of algal cultivation systems is claimed to be several times higher than the best performing land based crops. 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 and it is developing rapidly.

RENEWABLE OIL PRODUCTION PROCESS

UP TO 95% REDUCTION IN CO_2 VERSUS FOSSIL FUELS



TECHNOLOGY STATUS

The market for pharmaceutical and nutriceutical microalgae is well established and mature, albeit these products fetch a relatively high market price per tonne of end-user product (e.g. Spirulina), hence are less reliant on productivity and can be grown in simple, open pond systems. There are currently no known closed algal cultivation systems for biomass/biofuel production operating on a commercial platform as yet though there are many around the world emerging at pilot or demonstration scale. In short, it is no longer just an idea or laboratory experiment and several large global companies including BP, ExxonMobil, Chevron, Connoco Philips, Virgin Fuels, Anglo Coal and Royal Dutch Shell have invested heavily in research and are currently carrying out feasibility studies and trials with various systems.

RESEARCH STATUS

Research is broad and spans several decades of investigation – the idea is not new, but making it a commercial reality has been difficult, mostly due to inability to compete with vastly cheaper supplies of fossil energy. Research studies over the years have investigated a variety of cultivation and processing options and have identified numerous potential output markets. Research is also being done 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 out of it through application of efficient harvesting and processing techniques.

Since 2007, there has been an explosion of research institutes around the world that have turned their attention to 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.

PROJECT DEVELOPMENT

Numerous pilot and commercial demonstration projects are currently underway (reportedly 200 or more ventures exist); including retrofitting algae cultivation systems to power station exhausts. Sample projects/ventures include:

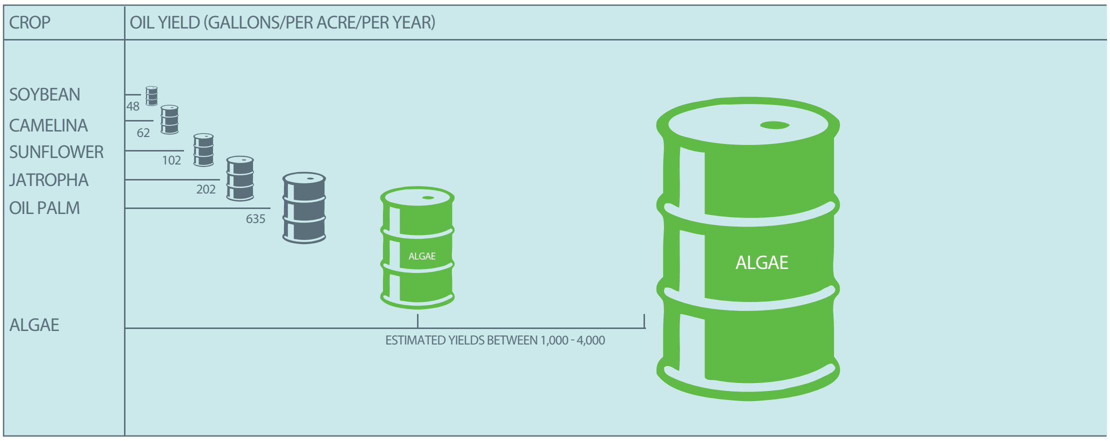
1. Algenol: An American company called Algenol (http://www.algenolbiofuels.com) is planning to develop an US$850 million algae plant in the Sonora Desert, with development set to begin in late 2010. It is estimated that around 6 million tonnes of CO_2 per year will be reused which will in turn produce up to 1 billion gallons of ethanol (170,000 acres at 6,000 gallons per acre). A supply agreement has been signed with Mexico's Federal Commission of Electricity (CFE). The sustainability of the project and potential success are very promising as the highest consumer of ethanol in the world is situated only 300 km away from the actual site e.g. the United States.
2. Solazyme: A novel process that doesn't use sunlight at all and grows algae in the dark using sugars. Solazyme's unique microbial fermentation process allows algae to produce oil in standard fermentation facilities quickly, efficiently and at large scale, without the limitations of surface area exposure to sunlight. The company 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.
3. MBD Energy: MBD's process uses algae to recycle captured industrial flue-gas emissions by conversion into oils, suitable for manufacture of high grade plastics, transport fuel and nutritious feed for livestock. MBD claim to have reached agreements for pilot plants to be established at three coal-fired power stations in Australia – Loy Yang A (Vic), Eraring Energy (NSW) and Tarong Energy (Qld) and now count Anglo Coal as a major investor. When fully operational, the pilot plants (on a per hectare, per annum basis) are estimated to be able to produce 140,000L oil and 280 tonnes of meal for energy production or stock feed, abating 800 tonnes of CO_2 in the process. Commercial scale operation is targeted for 2013 at an 80Ha scale, with a plan to introduce a demonstration plant by 2015.

CO_2 UTILISATION

Typically 1.8 to 2 tonnes of CO_2 will be utilised per tonne of algal biomass (dry) produced, though this varies with species and cultivation conditions. On a productivity basis, the following diagram compares algae to other forms of bio-oil derivatives, demonstrating its high conversion efficiency (Courtesy US DOE – Algal Biofuels Roadmap 2009):

SUPERIOR OIL YIELD COMPARED TO OTHER BIOMASS FEEDSTOCKS

COMPARISON OF OIL YIELDS FROM BIOMASS FEEDSTOCKS



Source: US Department of Energy - Algal Biofuels roadmap 2009

POTENTIAL MARKETS

There is potential to replace traditional petroleum derived products such as transport fuels with algae cultivated products through utilisation of the natural lipid fraction. 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. 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. 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.

SIZE OF MARKET

The likely use of the algae would be for the large scale production of biomass fuel which has a large potential market. It is forecast that by 2022 algae bio-fuels are the largest bio-fuel category overall, accounting for 40 billion of the estimated 109 billion gallons of bio-fuels produced

US MARKET

In 2009 the US produced 500 million gallons of biodiesel against a capacity of 2,200 million gallons.[10]

EUROPEAN MARKET

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.

10 Biodiesel 2020: Global market survey: Feedstock, Trends and Forecasts; Emerging Markets online (2008)

MARKET DRIVERS

A desire for energy security (specifically, transport fuel) and high volume CO_2 abatement are key drivers in the push for algal oil. Proponents argue that while a carbon price would be useful, it is not essential in the medium to long term given the projections for energy costs.

LEVEL OF INVESTMENT REQUIRED (TO ADVANCE THE TECHNOLOGY)

The use of recycled CO_2 for algae cultivation is still in the early research and development stages. There are currently no large scale algae cultivation projects in operation and the commercialisation of the technology is likely to require significant investment.

Algae farms are large and expensive with some researchers estimating capital costs of US$138,000 per hectare and US$43,800 per hectare per annum of operating costs (Campbell et al 2009). The further CO_2 capture and transport costs are likely to require additional capital and operating funding.

POTENTIAL FOR REVENUE GENERATION

If algae bio-fuels can be used as an alternative vehicle fuel then the revenue potential of the technology is significant, as even a modest share of the current petroleum market will result in considerable revenues.

PRICE SENSITIVITY

Prices are not likely to be competitive with crude oil equivalents until costs of algae cultivation and processing systems decrease or the price of crude oil increases. As yet to be fully commercialised, algae systems are highly exposed to fluctuations in the price of fossil crude, hence a need to also focus on additional market opportunities. A positive price sensitivity would be to the emergence of an international carbon price signal though most known players claim this is merely a 'sweetener' and their business models do not require this.

COMMERCIAL BENEFIT

Algae cultivation systems have potential to play a key role in the development of bio-refineries, where multiple products are produced from an integrated system using biologically derived feedstock – much like the oil refinery complexes of today. This enables adjustment of the business model to serve a variety of market opportunities as they change or emerge. The technology enables co-location with power stations on marginal land not otherwise useful for other forms of value creation or agricultural output.

BENEFITS

- Has high potential for very large scale reuse of CO_2.
- Algal oil can be injected into existing crude oil refineries.
- Use of algae derived energy carriers (bio-fuel, biogas) results in displacement of fossil equivalents.
- Can exploit point source emissions effectively (industry, stationary power generation), requiring little distance for transport and storage of CO_2 feed.
- Algae cultivation systems can be built on marginal land avoiding any competition with terrestrial food crops, an issue which has constrained first generation bio-fuels.

- Sewage waste-water can be utilised as a source of nutrients, reducing the burden on sewage treatment plants.
- The yield of an algae cultivation system is anticipated to be ten times higher per area of land compared to terrestrial vegetable oil crops (such as soy, canola, jatropha).
- Can offer a route to a carbon negative pathway, where carbonisation is used in processing to produce char.

BARRIERS

- Capital intensity of cultivation systems is currently a limiting factor.
- There are still significant technical and reliability barriers to overcome. At best it is anticipated this will be achieved in the next 3–5 years.
- Requires large amounts of nutrients similar to existing agricultural systems most of which are currently CO_2 intensive in production, though in a captive system these can be managed more effectively and 'recycled'.
- The reliability of systems must be proven for year round operation to ensure supply.

APPENDIX F: CO_2 AS FEEDSTOCK FOR CARBONATE MINERALISATION

OVERVIEW

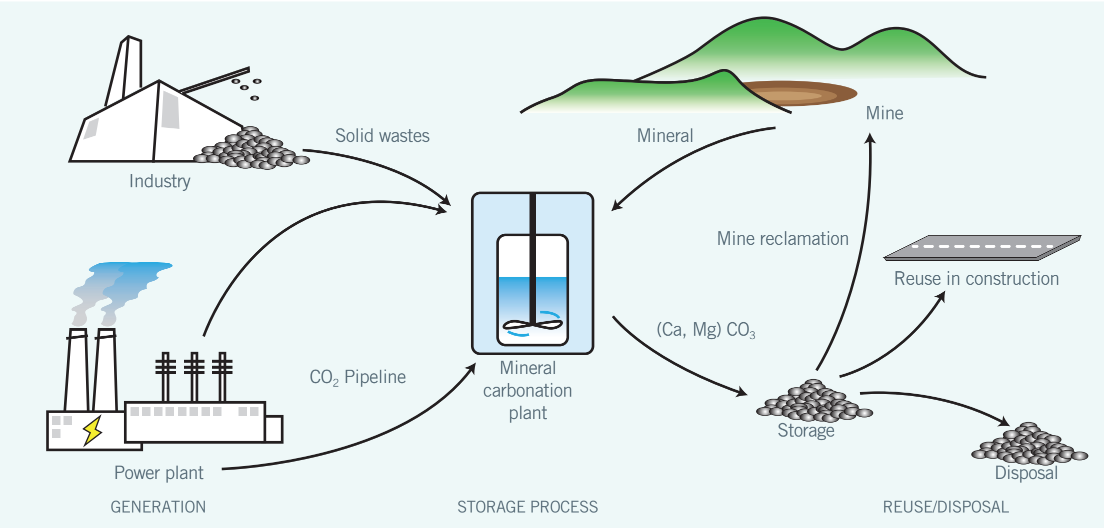
Carbon mineralisation is the conversion of CO_2 to solid inorganic carbonates using chemical reactions. In this process, alkaline and alkaline-earth oxides such as magnesium oxide (MgO) and calcium oxide (CaO), which are present in naturally occurring silicate rocks such as serpentine and olivine are chemically reacted with CO_2 to produce compounds such as magnesium carbonate ($MgCO_3$) and calcium carbonate ($CaCO_3$, commonly known as limestone). Mineral carbonation occurs naturally and is a very slow process. In order for carbonate mineralisation to be a viable method to capture and reuse CO_2 from anthropogenic sources such as coal-fired power plants, this process must be accelerated considerably.

Current research and development activities in carbonate mineralisation are focused on achieving energy efficient reactions and reaction rates viable for storage of significant volumes of CO_2 from industrial processes by using either:

- natural rock silicates; or
- industrial waste (fly ash and waste water/brine).

The carbonates that are produced are stable over long time scales and therefore can be used for construction, mine reclamation or disposed of without the need for monitoring or the concern of potential CO_2 leaks that could pose safety or environmental risks.

A flow diagram of the mineralisation process is presented below;



Process flow diagram for mineral carbonation[11]

11 Courtesy IPCC CCS Technical Summary report

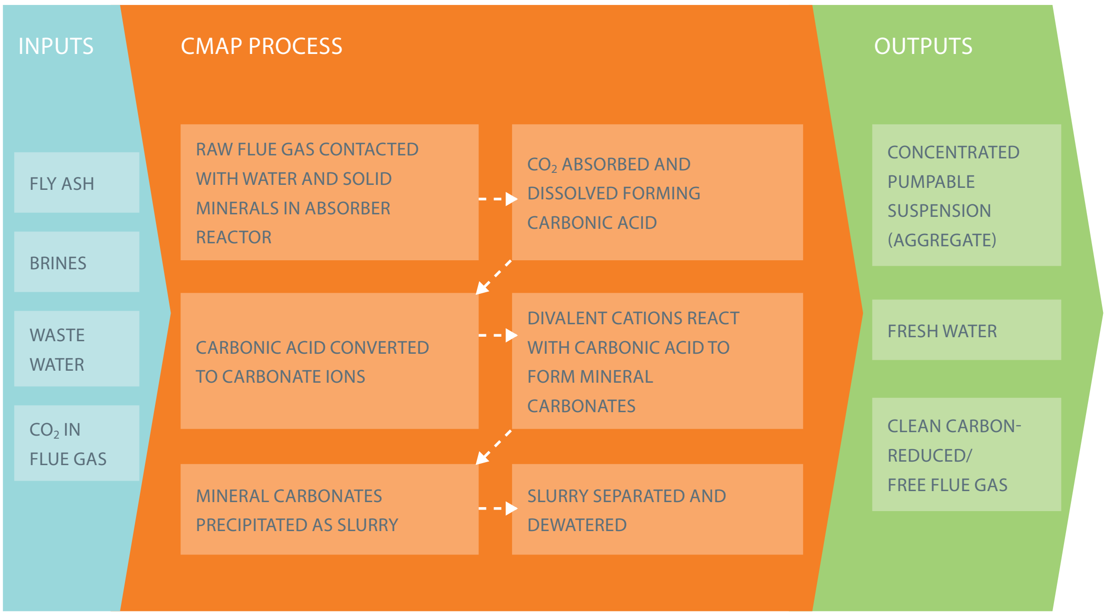
TECHNOLOGY STATUS

The use of natural rock silicates in mineral carbonation is still in the research phase. This technology involves utilising the abundance of magnesium silicates such as serpentine and olivine containing high concentration of MgO for the carbonation reaction. For this to be viable for commercial scale mineralisation requires:

- efficient extraction or activation of the reactive component MgO from silicate mineral; and
- acceleration of the carbonation chemistry kinetics.

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). The technology is also 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.

Carbonate mineralisation using industrial wastes (rather than natural rock silicates) are further developed with pilot scale plants in operation. In this process CO_2 emissions (from power plant flue gas or cement manufacturing process) are chemically combined with water/brine to form solid mineral carbonates and bicarbonates. In particular, Calera has successfully used fly ash as the source of alkalinity and for the production of cementitious materials (SCM), aggregate and other building related materials. The Calera carbonate mineralisation by aqueous precipitation (CMAP) process is shown below:



CALERA'S CMAP PROCESS

Calera has produced an alternative means of producing alkalinity in case there is an insufficient source or the available source is unable to complete the conversion of CO_2 to carbonate. The current process for the production of alkalinity (e.g. sodium hydroxide) uses the high energy demand chlor-alkali process. To overcome this problem Calera has developed a new low voltage technology, Alkalinity Based on Low Energy (ABLE) to generate sodium hydroxide. The process uses an electrochemistry process to split salt to form an alkaline solution and acid and reduces overall electrical demands by 60 per cent of the current generation technologies.

Skyonic's SkyMine® technology also removes CO_2 from industrial waste streams and produces solid carbonate and/or bicarbonate materials. There is limited public information on the status of the technology other then it has been field tested on operational coal-fired power plants.

PROJECT DEVELOPMENT

Currently two organisations are involved in developing the carbonate mineralisation technology using industrial emissions.

1. Calera is operating a continuous pilot scale facility in Moss Landing, California which produces on average 5t/day of supplementary cementitious material (SCM). A demonstration plant is under construction in which a 10MW slipstream from the 1.5GW Dynergy Moss Landing gas fired power plant will be used as the source.

   Calera is currently undertaking a pre-feasibility study for a demonstration plant at TRUenergy's Yallourn power station in the Latrobe Valley. It is reported that the project is due to start construction in 2010. The project plans to initially capture more than 300,000 tonnes of CO_2 per year and convert it into more than 1Million tonnes of building materials per year. The project will expand to capture 1.35M tonnes of CO_2 per year for conversion into 2.8M tonnes of building materials per year.

   Calera's business plan is for the construction of multiple demonstration plants to validate the commercial viability of its technology. Hence Calera Corporation and Bechtel Power Corporation have formed a strategic alliance to deploy Calera's technology worldwide.

   Calera is also currently constructing a pilot scale unit of their patented technology, Alkalinity Based on Low Energy (ABLE) which is capable of producing one tonne of NaOH per day. A demonstration scale unit consisting of fully commercial cells will be ready for operation in early 2011. This caustic production unit provides an alternative means of producing alkalinity for their CMAP technology.

2. Skyonic Corporation has developed SkyMine® technology, a carbon mineralisation process which removes CO_2 from industrial waste streams through co-generation of carbonate and/or bicarbonate materials. Phase 1 of Capitol-SkyMine demonstration facility has been initiated at Capitol Aggregates, Ltd cement plant in San Antonio, Texas, USA. Phase 1 includes modelling, simulation, design, costing, and procurement activities. Construction of the facility is anticipated to commence by the third quarter of 2010.

   The Capitol-SkyMine plant is targeted to capture 75,000 metric tonnes of CO_2 from flue gas and mineralize carbon emissions to produce 143,000 metric tonnes of baking soda. The mineralized carbon dioxide (baking soda) will be used in several industrial applications and will be tested as feed-stock for bio-algae fuels.

CO_2 UTILISATION AND RESOURCE QUANTITIES

Adsorption of one tonne of carbon dioxide using carbonate mineralisation based on natural rock silicates with high pressure and temperature CO_2 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 CO_2 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 (Sebastion Zevenhoven et al, 2007).

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 carbonation and cement formed by the Calera mineralisation process contains one-half tonne of CO_2.

POTENTIAL 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. Calera claim that CMAP 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.

SIZE OF MARKET

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 DRIVERS

Acceptance of products as replacement for existing aggregate and cement supply.

LEVEL OF INVESTMENT REQUIRED (TO ADVANCE THE TECHNOLOGY)

Calera plans to build a facility, Calera Yallourn, in the Latrobe Valley, Australia, which following a demonstration phase will be the first commercial scaled facility capable of capturing 200MWe of CO_2. The CO_2 will be captured from the flue gas of a local coal power station. Calera have estimated that the costs associated with the facility are as follows:

- CAPEX requirement (including CO_2 capture and building materials) of US$300-380m; and
- a cost of CO_2 capture of US$45-60/tonne of CO_2.

Details of further operating and maintenance costs are not available.

POTENTIAL FOR REVENUE GENERATION

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.

PRICE SENSITIVITY

The price of the technology will be affected by changes in demand for building products. The construction industry is typically cyclical so prices could be expected to vary over time.

COMMERCIAL BENEFIT

There are no significant commercial benefits of the technology since it is unlikely that the products produced via the process will be superior to existing products in the market. Therefore, the commercialisation of the technology will largely be driven by the environmental benefits. There is potential for the technology to have a higher commercial benefit in regions where exists carbon trading scheme exists.

BENEFITS

In general, mineralisation as a CO_2 reuse option has a number of benefits. The major benefit is the permanence of CO_2 storage. After mineral carbonation, CO_2 would not be released to the atmosphere and the silica and carbonates that are produced are stable over long time periods. As a consequence, there would be little need to monitor the disposal sites and the associated risks would be very low.

In particular, the Calera process which is one of the most advanced mineralisation technologies has a number of benefits. These include:

- The utilisation of waste streams such as fly ash and waste water.
- The technology does not require CO_2 separation or compression or CO_2 feed quality requirements.
- One of the by products is fresh water that could be used as potable water, irrigation water, or an industrial water supply, which may alleviate the water deficit in some regions.
- The process captures other emissions including sulphur dioxide, particulate matter, mercury and other metals.
- The core technology and equipment can be integrated with base power plants and cement manufacturing very effectively.
- Process is designed to utilise flue gas from a range of emission sources and can operate with a wide range of CO_2 concentrations.
- CMAP process removes hardness and other components from the brine, it allows for production of fresh water with lower energy consumption than raw brine. The separation of alkalinity, calcium, magnesium, and/or sodium chloride during the Calera process results in clean water that can be used as potable water, irrigation water, or an industrial water supply.

BARRIERS

The mass of natural silicate rocks (containing magnesium ore) to store CO_2 generated by coal combustion is calculated to be over eight times the mass of coal. Despite the large difference in mass, the mining operation is claimed to be of similar magnitude to that of coal (Herzog, 2002). Mineral carbonation using natural silicate rocks would be limited by:

- the fraction of silicate reserves that can be technically exploited;
- environmental consequences of large mining operation;
- environmental issues associated with the disposal of the carbonate (the volume of material increases as a result of the mineral carbonation process);
- legal and societal constraints at the storage location; and
- the energy intensity required for mining the resource and the carbonation technology itself.

It is likely that the carbonation process would need to take place at the mine, adding geographical constraints to this technology, raising similar issues to geological storage.

The Calera technology has the potential to be rejected by the cement industry (as it produces a product that is already produced in the manufacture of cement) and would require a carbon price to provide an incentive to cement manufacturers.

The success of Calera's CMAP technology for the development at the Yallourn site in Australia is highly dependent on the availability of suitable subsurface waters (brine) to provide the requisite hardness and alkalinity required and within abundant supply. Without such brines, alkalinity will need to be manufactured which raises concerns over the current status of the proposed ABLE technology which is still in early demonstration (pilot scale) phase.

APPENDIX G: CO_2 FOR CONCRETE CURING

OVERVIEW

New technologies and methods for cement production are reducing the production of CO_2 emissions from conventional Portland cement. Technologies such as the Calera process produce raw materials which may be used to supplant a portion of Portland cement. High tech firms such as Novacem (London), TecEco (Australia), C-Fix (Holland) and Calix (Australia) are new emerging competing companies focused 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/or by absorbing CO_2 from the atmosphere during the curing process.

Unique from the companies aforementioned, Carbon Sense Solutions (Canada) is seeking to use a point source of CO_2 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 CO_2 from onsite flue gases and local combustion sources to cure precast concrete products, with claimed equal material performance to traditional the curing process.

TECHNOLOGY STATUS

Extensive design and industrial testing is underway by Carbon Sense Solutions Inc. (CSS) to minimise the installation and operation risks in readiness for rapid acceleration from demonstration to commercial scale.

PROJECT DEVELOPMENT

Carbon Sense Solutions Inc. (CSS) is partnering with industry and the government to demonstrate and optimise the concrete curing process utilising CO_2 instead of heat and steam at an industrial scale. Extensive design and industrial testing is underway to minimise the installation and operation risks.

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.

CO_2 UTILISATION

CSS has indicated that up to 120kg of CO_2 per tonne of precast concrete is sequestered during the curing process. However, this figure may represent the total CO_2 offset that the technology can deliver.

POTENTIAL MARKETS

Concrete curing is a technology used by manufacturers of precast concrete worldwide. The main potential for the CO_2 curing method would be through the displacement of the traditional methods by existing manufacturers. Since, the flue gas produced by the concrete production process itself is a suitable source of CO_2, countries in which there exists a carbon scheme hold the most potential.

SIZE OF MARKET

Global cement production in 2009 amounted to 2.9 billion tonnes (Rusmet 2010), with corresponding concrete production well in excess of 10 billion tonnes. In the United States and Canada, annual cement consumption by the four main concrete products (masonry block, paving stone, cement board and fibreboard) is approximately 14 million tonnes (30 billion lb). If all of these products were carbonation treated, the net annual storage of CO_2 in concrete could reach 1.8 million tonnes (4 billion lb) using recovered CO_2 (at a net efficiency of 87.1 per cent) and 0.98 million tonnes (2.1 billion lb) using flue gas (at a net efficiency of 84.0 per cent)(Shao et al 2010).

MARKET DRIVERS

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.

LEVEL OF INVESTMENT REQUIRED (TO ADVANCE THE TECHNOLOGY)

Currently, CO_2 recovery costs about US$165/tonne (US$150/tonne) (US DOE, 2010). At this price, the CO_2 required for curing will cost about US$0.08 per masonry block (200 x 200 x 400 mm (8 x 8 x 16 in.) nominal size concrete masonry unit). Although the production of steam for curing currently costs only about US$0.02 per block, it is anticipated that the relative cost of CO_2 will decrease as recovery technologies develop and carbon storage credits affect the markets (Shi et al 2009).

POTENTIAL FOR REVENUE GENERATION

Use of CO_2 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 CO_2 as opposed to an alternative; however research suggests that with the current costs of carbon capture, the technology is more costly.

PRICE SENSITIVITY

The cost of the technology will be sensitive to the relative costs of CO_2 capture and those of materials required for alternative curing methods.

COMMERCIAL BENEFIT

Technology is in early stages of development however there is potential for the technology to be commercialised relatively easily as concrete curing process already exists in concrete production. Furthermore, research suggests that the flue gas produced from concrete plant itself may provide a suitable CO_2 source therefore reducing implementation costs. The commercial benefit in this case will be further incentive provided by the existence of a carbon trading scheme.

BENEFITS

Producers will benefit from energy and water reductions resulting in cost savings and efficiency gains.

Process is easily retrofitted, requiring targeted modifications to existing plant machinery with minimal disruption to existing processes.

It is claimed that the use of CO_2 results in an accelerated curing process with lower temperatures required.

BARRIERS

The concrete sector operates within a highly competitive commodity market with limited capital to invest in new technologies.

The change in production method (curing process) must not compromise material performance as the material performance is governed by industry standards (e.g. ASTM, CSA).

REFERENCES:

Scientific American (2008) Cement from CO_2: A concrete Cure for Global Warming?
http://www.scientificamerican.com/article.cfm?id=cement-from-carbon-dioxide
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APPENDIX H: CO_2 FOR USE IN BAUXITE RESIDUE CARBONATION

OVERVIEW

The extraction of alumina from bauxite ore results in a highly alkaline bauxite residue slurry (known as 'red mud'). The bauxite residue contains a mixture of minerals and some alkaline liquor (NaOH) from the Bayer extraction process. A new technology has been developed whereby concentrated CO_2 is used as a means of treating the highly alkaline by-product (pH=13) from the extraction of alumina. The process provides direct carbonation of the bauxite residue, locking up CO_2 and reduces the pH of the slurry to a less hazardous level.

TECHNOLOGY STATUS

The new bauxite residue treatment technology has been operating on trial at Alcoa's Kwinana refinery for several years. The plant uses waste CO_2 transported by a pipeline from a nearby ammonia plant. The plant locks up 70,000 tonnes of CO_2 per year and results in direct carbonation of Kwinana's entire residue by-product, which is typically between 2 and 2.5 million dry tonnes per annum.

Alcoa's patents on the technology have expired, but they are offering other alumina producers a 'technology transfer' package that includes their more detailed IP.

Alcoa have also recently patented an integrated carbon capture and residue carbonation process that would allow the use of flue gas from captive power generation plant emissions.

PROJECT DEVELOPMENT

Alcoa plan to deploy the technology to nine of their alumina refineries worldwide. Deployment across Australia alone is estimated to store 300,000 tonnes of CO_2 permanently each year.

CO_2 UTILISATION

Red mud treated with sea water has a large theoretical capacity to absorb CO_2 (up to 750kg CO_2/t red mud). However, Alcoa only proposes a level of 30-35kg of CO_2 per tonne of red mud (dry weight) as this is what is required to convert all of the alkalinity to carbonates.

Furthermore, Alcoa have raised concerns regarding the ability to retain the extra bicarbonate CO_2 within the residue.

POTENTIAL MARKETS

There is potential to implement the technology in Aluminium refineries around the world. There is also potential to neutralise the present excess stores of highly alkaline bauxite residue located in tailing ponds, to remove potential environmental risks and create a valued product. There is potential for neutralised bauxite residue to be used as road base, building materials or as soil amendment on acidic soils.

SIZE OF MARKET

Worldwide over 70 million dry metric tonnes of bauxite residues are generated annually when alumina is extracted from bauxite ore. Globally more than 200 million tonnes of bauxite residue has accumulated, the majority of which is stored in tailing ponds.

POTENTIAL FOR REVENUE GENERATION

There is little potential for direct revenue generation as the resulting neutralised bauxite has little commercial value. The potential for economic feasibility should instead be based on the potential savings associated with the handling, transportation and storage of the neutralised product over the original alkaline residue.

COMMERCIAL BENEFIT

At present, the highly alkaline bauxite residue is simply a by-product of the alumina production process and has no commercial use. A potential benefit is the use of the neutralised residue as a soil amendment. Although it is likely that the bauxite will have little commercial value (and essentially be offered free to the agricultural sector), the real commercial value will arise from the costs saved from negating the need to store the unwanted residue. A Bauxite Residue Sustainability report released by Alcoa suggests a benefit (reduced tailings management cost) equivalent to over AU$20/t of CO_2 utilised.

BENEFITS

Benefits of re-using CO_2 to neutralise bauxite residue include:

- The residue with a pH level of about 13.5 has limited potential for reuse, presents an environmental risk and is required to be stored in lined storage areas. By mixing concentrated CO_2 through the bauxite residue the pH is reduced to 10.5, presenting a significantly lower environmental risk and the potential for reuse as road base, building materials or to improve soils.

BARRIERS

There are a number of barriers which will affect the value for money of widespread implementation of the technology including:

- high purity of CO_2 required;
- locality of CO_2 source;
- no prospects for revenues as a result of production of useful by-product; and
- relatively low levels of CO_2 storage.

Technology has not received any government funding/grants.

APPENDIX I:
CO_2 AS A FEEDSTOCK FOR LIQUID FUEL PRODUCTION

OVERVIEW

CO_2 as a feedstock for liquid fuel production is a broad category for CO_2 reuse, which includes conversion of CO_2 to a number of alternative fuel products, including formic acid, methanol, dimethyl ether, ethanol, and other petroleum equivalent products. To produce these varied end products, a range of CO_2 conversion technologies are proposed.

In general the primary energy input for these conversion technologies is renewable energy, with the current proponents focused on solar and geothermal energy. This is an important requirement for these technologies, as generally they have relatively low thermal efficiency (e.g. relatively small fraction of the energy input is converted to useful fuel). Consequently, the primary energy input needs to have a low CO_2 emissions intensity. If fossil-fuel based energy were used as the primary input into CO_2-based liquid fuel production, more CO_2 would be released than if the fossil fuel were used directly as a fuel.

TECHNOLOGY STATUS

Proponents have developed their technology to widely differing extents. Some processes / solutions are only beginning to be investigated in laboratories and with laboratory scale demonstration reactors. On the other hand some companies claim to be commercialising their respective CO_2 to fuels technology, whilst at least one company (Carbon Recycling International) is constructing a commercial project.

Technologies at the fundamental research stage are predominantly being developed in the United States. For example, Pennsylvania State University is exploring the performance of titanium dioxide nanotube catalysts in the sunlight driven conversion of CO_2 and H_2O to methane and other light hydrocarbons, and Sandia National Laboratories has constructed a prototype device (the Counter Rotating Ring Receiver Reactor Recuperator, 'CR5') for high temperature solar conversion of CO_2 and H_2O to syngas using a metal oxide catalyst.

Technologies beyond the fundamental research stage are listed in the table below.

ORGANISATION	FUEL PRODUCT	TECHNOLOGY STATUS
Carbon Sciences, USA	Light hydrocarbons	Moving from laboratory towards commercialisation
Joule Unlimited Inc (Joule), USA	Ethanol and diesel equivalent products	Moving from laboratory towards commercialisation
Mantra Venture Group (Mantra), USA	Formic acid	In negotiations for first commercial demonstration
Carbon Recycling International (CRI), Finland	Methanol	Constructing first commercial plant

CARBON SCIENCES, USA

Carbon Sciences claim to have developed enzyme-based biocatalyst technology for conversion of CO_2 & H_2O to light hydrocarbons (methane, propane, butane). The light hydrocarbons can then be further processed to liquid fuels. Publicly available information relating to Carbon Sciences technology is extremely limited, but it is stated that the process is executed at low pressure and temperature.

Carbon Sciences has made claim to multiple patent applications in recent years, but a comprehensive search of the US Patent and Trademark office has failed to locate such patent applications. No response was received from Carbon Sciences following a request for information. A formal evaluation of Carbon Sciences is not possible given the information void that exists around the technology.

JOULE UNLIMITED INC. (JOULE), USA

Joule claims to have developed product-specific photosynthetic organisms that produce hydrocarbons as a by-product of metabolism, and that survive in brackish water. Joule has not publicly released a detailed description of the specific micro-organisms they intend to utilise in commercial applications. A review of their patent application material suggests it could be a genetically modified strain of bacteria, though a range of other possibilities exist (yeasts, enzymes etc.).

Joule's primary energy input to the conversion process is un-concentrated solar energy. Joule claim their technology has the potential to yield 25,000 gallons of ethanol per hectare, which for a plant located in an area with a good solar resource (for example, California) equates to an overall solar energy conversion efficiency of 2.4 per cent. This is not dissimilar to the energy conversion efficiency of biomass crops.

With reference to illustrations on Joule's website, along with articles in the press, it is possible to determine that Joule's organisms circulate within glass reactors supported with a steel frame. This kind of arrangement is capital intensive, with analogies to be drawn with the costs of solar thermal arrays.

Joule differentiates themselves from algal biomass production, highlighting the fact that they don't produce biomass (or at least the biomass: oil production ratio is very low). No response was received from Joule following a request for information.

MANTRA VENTURE GROUP (MANTRA), USA

Mantra's technology produces formic acid by direct reduction (electrolysis) of CO_2 in water. It requires an electrical energy input of 8MWh/t CO_2, which represents an electrolysis efficiency of 20 per cent when the energy content of the end product (formic acid) is considered.

CARBON RECYCLING INTERNATIONAL (CRI), FINLAND

CRI's technology produces methanol by catalytic reaction of CO_2 and H_2. CRI is presently constructing a commercial demonstration plant in Iceland.

H_2 is produced via electrolysis of water. Modern systems for electrolysis of water may have efficiency in the vicinity of 65 per cent. A concentrated stream of CO_2 is developed using conventional capture technology applied to an industrial source. According to CRI patent material, the two gas streams are combined and compressed to approximately 5MPa before entering a reaction loop where the mixture is heated to ~225°C, reacted over a metal/metal oxide catalyst to produce methanol and water (equilibrium composition ~20 per cent to 25 per cent), passed through a counter-flow heat exchanger, then though a condenser where the methanol and water are separated out. Following the condenser the gas stream is combined with new feed gas, passes back through heat exchanger and returns to the reaction vessel. PB estimates the thermal efficiency of the catalytic process is 75 per cent or better.

CRI's preferred embodiment is probably a conventional geothermal power station, as it is a low-emission source of electricity that still produces enough CO_2 (typically) to use as a feedstock for the methanol production process.

PROJECT DEVELOPMENT

Carbon Sciences – there are no projects identified.

Joule recently closed an US$30 million funding round, with the proceeds to be directed towards pilot plant operations at Leander, Texas. Joule is claiming a system that will be commercial-ready by 2012.

Mantra advises that a demonstration project in South Korea is planned to commence shortly. No further information is available regarding the size, cost, or exact location of the project. Korea has a grid emissions intensity of 444kg CO_2/MWh.

CRI is currently constructing a 4.2 million litre per annum commercial demonstration plant in Iceland. Publicly available information suggests the renewable methanol plant will be located adjacent to the 76.5MW Svartsengi Geothermal Power Station, which will in effect be the source of power and CO_2 (and potentially water) for the project. Note that Iceland has an estimated grid emissions intensity of ~310kg CO_2/MWh. If the power supply to the renewable methanol project is considered to be solely from the Geothermal Plant (rather than from the grid), then the emissions intensity will be lower still (~171kg CO_2/MWh), and will further benefit from the capture of a portion of the plants CO_2 emissions for methanol production (down to 173kg/MWh). The CO_2 will be captured using an amine solvent process.

Methanol will be blended with conventional unleaded petrol and sold at Olis gasoline stations throughout the greater Reykjavik area. CRI has stated that Iceland is an attractive location for project development because the petrol: electricity price ratio is one of the highest in the world – obviously a key measure of the likelihood of success for fuel synthesis projects based on electrolysis.

POTENTIAL MARKETS

As a replacement for fossil fuels, the potential market for CO_2 derived fuels is large, and global. Consumption of fossil fuels for transport in 2007 was 2297 Mtoe (Million tonnes of oil equivalent).

MARKET DRIVERS

The main driver to support the commercialisation of the technology is the potential to penetrate the transportation energy market which is expected to see significant growth in the forthcoming years.

PRICE SENSITIVITY

The price will be sensitive to the economics in supply, demand and price of petroleum and other alternative fuels.

COMMERCIAL BENEFIT

The main commercial benefit of this technology is to provide an efficient fuel for wide scale use in the transportation sector. It is highly likely that the current transportation fuel sources (namely derived from fossil fuels) will be unable to meet the forecast demands in the forthcoming years hence, commercialisation of this technology would enable it to capitalise on the energy shortfall.

BENEFITS

In an ideal embodiment of the CO_2 to liquid fuels concept, the CO_2 feedstock is converted into an energy carrier, but the energy input is renewable or has very low CO_2 emissions intensity. The ideal embodiment gives potential for a reduction in CO_2 emissions as compared to the combination of an uncaptured CO_2 and fossil-fuel based economy.

Proponents argue that the ability to use existing petroleum-based infrastructure (transport, distribution, storage, engines, and vehicles) is a benefit of the CO_2-to-liquid fuels approach, assuming the liquid fuels produced are comparable to petroleum diesel or gasoline (which is not always the case).

The widespread use of this technology will help governments meet their targets for low and zero-emission vehicles.

BARRIERS

Some critical barriers include the low efficiency and high capital cost that is a characteristic of some of the CO_2-to-liquid fuel technologies. It is likely that some technologies will never overcome these cost barriers and will consequently not be commercial.

Furthermore, here we are focused on the conversion of CO_2 to a liquid fuel, with the transport sector as the main market. A potential barrier is that alternative transport systems (such as electric vehicles with regenerative braking coupled to a renewable energy powered electricity grid) may be a more competitive solution, with significantly higher overall energy conversion efficiency. At present, electric vehicles already have lower running costs than petroleum fuelled equivalent vehicles thanks to the relatively low cost of off-peak grid electricity and the benefits of regenerative braking. It is possible that in the longer-term electric vehicles will prove to be significantly cheaper.

APPENDIX J:
ENHANCED COAL BED METHANE RECOVERY

OVERVIEW

Coal bed methane (or coal seam methane) is a mixture of mainly methane, and trace quantities of light hydrocarbons, nitrogen, and CO_2, which are generated during the geological transformation from peat to anthracite coal in underground coal seams. The gas is adsorbed onto micro-pores on the surface of the coal, and exists in a near-liquid form at high pressures. The amount of gas which is generated and trapped within the coal depends on the quality and permeability of the coal, and the pressure and depth of the coal seam, but it can be generated in excess of $100m^3$ per tonne of coal formed.

Conventional coal bed methane extraction is achieved by dewatering and reducing the pressure in the coal bed, such that adsorbed methane is released from the porous coal surface. Conventional coal bed methane extraction may leave up to 50 per cent of the methane in the seam. In CO_2-ECBM, CO_2 is preferentially adsorbed on the porous coal surfaces, releasing additional methane in the process.

This adsorptive storage mechanism is considered verifiable. Further confidence in storage permanence may be attributed to the cap rock formation having already been verified as an effective trapping mechanism throughout the methane production process, which takes place over millions of years.

TECHNOLOGY STATUS

Commercial production of coal bed methane is currently limited to conventional extraction e.g. without the use of CO_2.

ECBM technology is still in the development phase, though this is in large part due to current lack of commercial incentive for the process, as opposed to any insurmountable technical hurdles. The most high-profile ECBM pilot was located in Alberta, Canada, which commenced in 1997 and was focused on research and development into single and multi-pilot wells, optimising working fluid properties, matching CO_2 sources with suitable sinks in the region, and environmental and verification monitoring.

RESEARCH STATUS

There are several research projects currently underway to further develop ECBM;

Research is being carried out in the US by the Department of Energy, in Canada by the former Alberta Research Council (now Alberta Innovates), in Australia by the CSIRO, in Switzerland by ETH and, in the UK, the Netherlands and China. Research is aimed at discovering the many unknown variables in the ECBM process and to understand the modelling characterization of a single and multi-component adsorption/desorption behaviour of different coal types.

In the US, a US DOE sponsored pilot project in Marshall County, West Virginia, and being undertaken by Consol Energy will inject up to 18000t CO_2 over an approximately two-years into horizontal wells, with useful data to be gathered on gas production and composition, and monitoring of the site to continue for two-years after injection ceases. Injection commenced in 2009.

Earlier in 2010, CSIRO announced a CO_2-ECBM demonstration project in China partnering with China United Coal Bed Methane Corporation Ltd (CUCBMC) and supported by JCOAL, Japan. The project plans to inject 2000t CO_2 into the Liulin Gas Block, Shanxi Province at a depth of approximately 500m, and investigate the effect of horizontal drilling through the coal seams, with increased CO_2 flow rates predicted.

The former Alberta Research Council (now part of Alberta Innovates – Technology Futures) is involved in a joint project with CUCBMC in the south Qinshui Basin of Shanxi Province in North China, this pilot project is testing the viability of storing CO_2 in deep, unmineable coalbeds, and of enhancing coalbed methane recovery by CO_2 injection. In the initial (completed) phase of the project, 192 tonnes of liquid CO_2 were injected into a single coal seam in 13 injection cycles, soaked, and produced back. Future phases of the project involve the design and implementation of a multi-well pilot and evaluation of the commercial prospects of the ECBM technology.

Another project development has been in place in Alberta, Canada since 1997 and is ongoing in an area where there are abundant coal-bed methane sources, but little commercial activity in the industry as a result of low permeability. The area covered is 20–40 acres in which 5 injection wells are installed, testing the adsorption of CO_2 from a coal seam situated at a depth of 500 meters. This project has many major participants including; Air Liquide Canada, BP, Environment Canada, Japan Coal Energy Centre, Netherlands Institute of Applied Geoscience, Sproule Industry, Suncor Energy Inc., Tesseract Corporation (USA), UK Department of Trade & Industry and the US Department of Energy. The research was undertaken with initial pilot studies and the feasibility of CO_2 and N_2 injection ratios to improve ECBM recovery rates. The project learning's suggest that even in tight reservoirs, continuous CO_2 injection is possible and that in effect, the injected CO_2 remains in the reservoir while increasing sweep efficiency.

Further research into ECBM is currently being encouraged by western governments and is expected to grow and develop greatly in the coming years. This could subsequently lead to the creation of projects focused mainly in the developed world where coal beds, carbon point source locations, energy demand and storage regulations are favourable to ECBM application.

PROJECT DEVELOPMENT

Project development is limited. Most projects underway would be considered research, pilot or small scale demonstration projects. No commercial projects are presently being developed.

The most referenced prior commercial scale CO_2-ECBM demonstration/project was the Allison Unit ECBM Pilot, located in San Juan County in southern New Mexico. The Allison Pilot was part of the US DOE funded Coal-Seq project, operated by Advanced Resources International and Burlington resources and consisted of 4 injection wells and 16 producer wells, injecting approximately 335,000 tonnes of CO_2 between 1995 and 2001, with incremental methane recovery of approximately 30,000 tonnes. Burlington has not rolled out ECBM across the remainder of their coal seams in the San Juan Basin.

CO_2 UTILISATION

CO_2 utilisation rates will depend on the nature of the coal seam, in particular the storage ratio (the ratio of CO_2 adsorbed to CBM desorbed) and the pressure of the seam. For high volatile bituminous coals at low to medium pressures, the storage ratio is approximately 2:1. For lower quality coals at the same pressure, the storage ratio increases to approximately 8:1, and can be as high as 13:1 for lignite.

It has been estimated that there is the potential to increase worldwide CBM production, utilising ECBM, by 18 trillion cubic metres, while simultaneously sequestering 345Gt of CO_2 (Massarotto et al, 2005).

Results from research held in 29 sites for potential CBM and ECBM in China have determined that CO_2 storage potential is about 143Gt in the countries coal bed. This could sequester CO_2 emissions for an estimated 50 years based on China's CO_2 emission levels in 2000. Simultaneously, the production of methane from ECBM has been estimated to reach 3.4 and 3.8 Tm^3 respectively, which equates to 218 years of production at China's 2002 production rates (Hongguan et al., 2006).

In the Netherlands, 3.4 Mt of CO_2 from chemical installations could be sequestered, as well as 55Mt from power plants. Four potential ECBM areas were assessed, where it was estimated that between 54Mt – 9Gt of CO_2 could be sequestered between all four – depending on the technological advances for coal seam access (Hamelinck et al., 2002).

Studies have carried out evaluations of CO_2 and flue gas injection scenarios, showed that an injection of 100 per cent CO_2 in an 80-acre five-spot pattern indicate that low-rank coal can store 1.27 – 2.25 Bcf of CO_2, whilst ECBM recovery reached levels of 0.62 – 1.10 Bcf. Simulation results of flue gas injection composed of 87 per cent N_2 and 13 per cent CO_2 indicated that these same coals can absorb CO_2 levels of 0.34–0.59 Bcf at depths of 6,200 ft, whilst ECBM recovery reached levels of 0.68 – 1.20 Bcf (Hernandez et al., 2006).

POTENTIAL MARKETS

ECBM as a technology is region specific, requiring proximity of point source emitters of CO_2 and suitable coal seams. Market opportunities exist within the US, Europe, New Zealand, Canada, Australia and most of the developed world with high coal levels. The technology could progress to developing countries with large coal reverses, although this is expected to happen once research is more advanced and projects in the developed world have proved successful. Favourable conditions such as coal bed and carbon point source proximity, energy demand and storage regulations will help market drive.

The Chinese are currently very interested in this technology as a result of their high dependence on coal power plants. The potential for this technology to spread in China is massive, considering storage through ECBM could store 50 years of China's CO_2 emission, based on 2000 levels, once the technology has been developed more widely.

US MARKET

The abundance of deep coal beds in the US presents strong market opportunities for ECBM. In 2009, more than 1,170 million tonnes of coal was mined, more than at any other time in US history. Last year the US Energy Information Administration estimated that the remaining US recoverable coal reserves at just less than 263 billion tonnes.

The US currently has projects researching the ECBM process in Alabama (Black Warrior). The US Department of Energy has committed itself to this research, which strengthens the view that there is a good opportunity in the US for this market.

EUROPEAN MARKET

Coal is mined in significant amounts in various European states. Research that has taken place into ECBM, for example projects in the Upper Silesian Basin of Poland (RECOPOL project funded by the EC) and the Sulcis Coal Province in Italy, and prospects in the UK continental shelf and in Russia and Ukraine, amongst others, suggest real market opportunities in Europe.

DEVELOPING COUNTRIES

There are large coal basins in various other countries that have significant ECBM potential, for example China, India, and Indonesia. However there is not much detailed information available on ECBM development so far in these, and other, developing countries.

MARKET DRIVERS

The main market drivers for this technology are natural gas prices and a potential carbon emissions trading scheme, with higher pricing for each providing a greater driver for deployment of CO_2-ECBM.

LEVEL OF INVESTMENT REQUIRED (TO ADVANCE THE TECHNOLOGY)

Little information is available regarding the level of investment that would be required to advance ECBM technology. Although the technology has operated at a commercial demonstration scale from 1995, the technology is still in the development phase and research is continuing. The total amount required is likely to be significant.

POTENTIAL FOR REVENUE GENERATION

The revenue generation of ECBM will be dependent on a number of factors and will largely be affected by the individual locations and quality of the individual sites. The main drivers affecting the profit potential include cost of CO_2, value of methane, cost of processing, cost of implementation and transportation.

PRICE SENSITIVITY

The pricing of the projects, including the technology and the potential revenues, will be affected by the same factors as mentioned above.

COMMERCIAL BENEFIT

The commercial benefit of ECBM is potentially very strong, tapping into the energy market to meet high energy demands with methane. The coal-bed methane industry represents a substantial market for CO_2, especially if the CO_2 is readily available from local coal-fired power plants to produce CO_2 in enough quantity to facilitate enhanced coal-bed methane recovery at a large scale.

As has been discussed, ECBM technology would have to improve to ensure economical recovery.

BENEFITS

ECBM could deliver many potential benefits, including;

- Significant increase in natural gas production through ECBM for both feedstock and product considering an approximate 2:1 injection ratio is required. In China, as an example of a country with large coal reserves, ECBM could generate 3.8Tm^3 of natural gas, equalising 218 years of production based on China's 2002 levels.
- Environmental benefits through burning methane (the cleanest of the fossil fuels) to meet energy demands instead of through burning carbon rich fuels, such as coal.
- Employment opportunities in regions and countries where ECBM is applied.

BARRIERS

The barriers to widespread ECBM development include:

- research is still at a development level, with further studies and research required to understand the fundamental issues related to ECBM, particularly around the modelling of a single and multi-component adsorption/desorption behaviour of different coal types;
- ECBM is location specific, while preparation of a potential ECBM sites requires extensive study and development. This presents high costs barriers and currently limits expansion of the technology into green field sites; and
- higher natural gas prices are likely to be required.

APPENDIX K: EVALUATION SCORES

TECHNOLOGY: ENHANCED OIL RECOVERY	DATE: 23/06/10

Technology Definition:

Enhanced Oil Recovery (EOR) is a tertiary oil production stage, which involves flooding oil reservoirs with injected CO_2 to displace oil contained within, increasing oil recovery by 7–23 per cent from primary extraction.

Proponents:

Companies employing EOR technology for capture on industrial plants (e.g. syngas, natural gas sweetening, coal power, fertiliser, or cement production) and in transport range of suitable oil wells, with existing demonstration size or greater EOR projects, include:

Andarko Petroleum Corporation (Salt Creek, USA), Chevron (Rangely-Webber EOR, USA), the Chinese Government (Daqing EOR, China), EnCana (Weyburn, Canada), Penn West Energy Trust (Pembina Cardium EOR, USA).

ITEM	SPECIFIC SUB-CRITERION	SCORE	EVALUATION COMMENTS
Technology Maturity			
1.01	Timeframe to deployment	3	CO_2 for EOR is a proven technology, first applied in the early 1970s in Texas, USA and has since been developed constantly and applied in many parts of the world. Due to this, EOR with CO_2 can be considered at a commercial stage of development.
Scale-Up Potential			
2.01	Scale-up potential	3	In North America where CO_2-EOR is most widely employed, the Department of Energy (DOE) estimated around 50 Mt CO_2/yr is currently used. Considering most proven wells are in production decline, operating companies and governments a like will seek to limit reliance on foreign oil and gain the revenue from known resources. With this driving CO_2-EOR, the global scale-up potential could exceed 300Mtpa if large oil producing countries, such as the Middle East, widely adopt EOR when primary oil production ceases and tertiary extraction methods are needed to extend reservoir life.
2.02	Geographical constraints on the production system	2	CO_2-EOR is very specific to location. CO_2 source, transport options and associated cost compared to the revenue of increased oil produced determine if EOR is a cost effective way to extend well production life.

ITEM	SPECIFIC SUB-CRITERION	SCORE	EVALUATION COMMENTS
Value for Money			
3.01	Commercial viability	3	CO_2-EOR is an established technology and existing projects prove its commercial viability. There is a large potential for use of CO_2-EOR to be used in many of the worlds oil fields however economic feasibility will be dependent on the amount of oil which can be recovered from the individual site, the prevailing price of crude oil and the regional costs of implementing the technology.
3.02	Competitiveness with other emerging technologies	3	EOR technology can be implemented using CO_2, water or nitrogen as the transmission fluid and there is potential for CO_2 to replace the use of water or nitrogen in a number of regions. This could be particularly highlighted in regions where water is traditionally sparse and therefore a valuable commodity. The CO_2 storage potential of depleted oil fields following EOR will likely affect demand for the use of CO_2 in countries which have a carbon capture scheme.
3.03	Barriers / Incentives / Drivers	2	The main value for money barriers associated with CO_2-EOR include: • Uncertainty over the amount of oil which can be recovered using the technology; • High capital and operating costs of implementing technology; • Uncertainty of future crude oil prices and therefore profits. The main drivers for the use of CO_2-EOR are: • increased oil recovery from existing resources; • extending the useful economic life of oil fields; and • capitalising on carbon capture schemes by offering permanent storage of CO_2.

ITEM	SPECIFIC SUB-CRITERION	SCORE	EVALUATION COMMENTS
CO_2 Abatement Potential, Environmental and Social Benefits			
4.01	Permanence of Storage	2	The EOR process involves CO_2 being injected into an oil reservoir and displacing oil to the surface. During this application, more than 50 per cent and up to 67 per cent of injected CO_2 will return to the surface with the extracted oil, requiring separation and reinjection into the well to prevent release into the atmosphere. Operating cost through not requiring additional CO_2 is also reduced by re-injection. The remainder of the injected CO_2 remains sequestered in the oil reservoir, including when EOR is complete and oil production ceases.
4.02	Additional CO_2 emissions from reuse	2	CO_2 injection per oil displacement rate is very dependant on reservoir characteristic (e.g. size, pressure, temperature, oil weight, etc) so varies dramatically and would need to be examined on a site by site basis. Assuming US grid power dependence to capture, compress and inject CO_2 from a point source, for every tonne of CO_2 injected into a well, 310 kg CO_2 is released from power generation with a carbon density of 0.89 tCO_2/ MWh, to supply the CCS chain with 350 KWh/tCO_2 injected. Emissions for subsequent use of oil are not included. Edge Environment Case Study Result: 0.51t CO_2-e/t reused. Case Study Description: Capture from a coal-fired power station near the Dakota Gasification Plant in the USA, delivered via pipeline to the Weyburn CO_2-EOR flood (e.g. surface processing and reinjection power comes from the Canadian Grid).
4.03	Environmental Benefit (Non CO_2 abatement related)	0	No additional specific environmental benefits have been identified.
4.04	Social Benefit (Non CO_2 abatement related)	0	No specific social benefits have been identified.

ITEM	SPECIFIC SUB-CRITERION	SCORE	EVALUATION COMMENTS
Developing Countries			
5.01	Applicability to developing countries	2	Through aggressive greenhouse gas (GHG) reduction targets, Western governments are supporting the development of CCS by funding demonstration projects, with the aim of seeing CO_2 capture and storage from industrial applications become economically and technically viable for widespread deployment. CO_2-EOR is considered a stepping stone in this process in which revenue can be generated to help support the cost of CCS implementation and operation. EOR is equally applicable to developing nations as its use can be economically viable without a carbon price so could be applied to an oil reservoir anywhere in the world, which is close to a point source of carbon if a return on investment will be generated.

TECHNOLOGY: BOOSTING YIELDS OF CONVENTIONAL FERTILISER PRODUCTION FACILITIES	DATE: 10/06/10

Technology Definition:

Urea ($(NH_2)_2CO$), a nitrogen fertiliser, is produced by the reaction between ammonia (NH_4) and CO_2. The final product is a prilled or granulated solid which once applied to agricultural land in solid or liquid form reacts with water to release the CO_2 and ammonia (NH_4). Ammonia absorbed through the roots and/or foilage and is used as a nitrogen source for the plant.

Proponents:

Many companies globally. China and India produce the largest amount of urea, approximately 47 per cent.

ITEM	SPECIFIC SUB-CRITERION	SCORE	EVALUATION COMMENTS
Technology Maturity			
1.01	Timeframe to deployment	3	Urea has been produced on an industrial scale for over 40 years. The technology is well understood and can be considered mature. CO_2 capture from natural gas boiler on urea plant is relatively new MHI have several units operational in the several 100's tpd CO_2 range.
Scale-Up Potential			
2.01	Scale-up potential	1	The current market for urea is 159.4Mtpa (equivalent to approximately 119.6Mtpa CO_2) according to the International Fertiliser Association. Typical surplus ammonia from Natural Gas based Urea plants is approximately 10 per cent. If all current surplus ammonia was reacted with CO_2 to produce Urea, only 9Mtpa CO_2 would be required. Over half the recently constructed urea plants use coal as a feedstock, which generates a surplus of CO_2 rather than a surplus of ammonia. Even with significant increase in global manufacture of Urea, the requirement for additional CO_2 is limited.
2.02	Geographical constraints on the production system	3	Constrained by upstream ammonia plant. Also, ammonia plant ideally located near source of natural gas or coal. Urea is classified as non hazardous and is produced in solid granules or liquid, it is readily transported in bulk or in Intermediate Bulk Containers (IBCs).

ITEM	SPECIFIC SUB-CRITERION	SCORE	EVALUATION COMMENTS
Value for Money			
3.01	Commercial viability	2	The production of urea is an established technology with a proven commercial viability. However, the use of recycled CO_2 from industrial sources is not yet commercially operating. The concept is currently being tested by MHI (Mitsubishi Heavy Industries Ltd). Here CO_2 from flue gas emitted during the urea fertiliser production process is provided as feedstock for urea synthesis by Ruwais Fertilizer Industries (FERTIL), a fertiliser producer in the United Arab Emirates. The technology can recover approximately 90 per cent of the CO_2 in flue gas. The plant is due to open in 2010. This project is likely to test the economic and commercial feasibility of the use of recycled CO_2 for the urea production. It is possible that carbon captured from flue gas may be a commercially viable source of CO_2 for urea production. However global commercial viability may be limited to agricultural areas where there is co-location of urea production plant and suitable CO_2 source.
3.02	Competitiveness with other emerging technologies	2	Nitrogen fertiliser is a product with an established global market with current urea prices at $225-$290 per tonne. In order to enter the market then the urea produced using recycled CO_2 needs to be at or below the current market prices, after processing and transport costs. MHI Ltd's project in the UAE is estimated to cost $1.2–1.5bn. This includes building a 2,000-tonne-a-day (t/d) ammonia plant and a 3,500-t/d urea train alongside Fertil's existing complex. Details of the anticipated operating and urea production costs at this site are not currently available. The UAE project benefits from the co-location of the CO_2 source and the urea production plant and so does not require additional costs associated with the transportation and storage of CO_2. Further investigation into the estimated costs of CO_2 transport and storage, which may be highly costly, will need to be considered when assessing the price competitiveness of the technology against existing alternatives.

ITEM	SPECIFIC SUB-CRITERION	SCORE	EVALUATION COMMENTS
3.03	Barriers / Incentives / Drivers	2	The main barriers associated with the use of recycled CO_2 in urea production include: • the volatility of in the price and demand of urea and ammonia makes long term appraisal difficult; and • the potential high capital costs of CO_2 capture infrastructure. The main driver in determining the value for money of the technology is likely to be determined by the forecast demand and supply of urea and ammonia.
CO_2 Abatement Potential, Environmental and Social Benefits			
4.01	Permanence of Storage	1	Once applied to the land and contacted with water the reaction used to form urea is reversed, the ammonia produced is absorbed by the plants and the resultant CO_2 is released to atmosphere, meaning CO_2 has a short period of storage. The permanence of storage for CO_2 contained in urea which is further processed for example in the chemical industry is dependant on the process and the nature of the final product, this however accounts for a small amount of urea use.
4.02	Additional CO_2 emissions from reuse	1	The production of urea consumes CO_2 at the rate of 0.735-0.75 tonnes of CO_2 for every tonne of urea produced. However this CO_2 is only stored temporarily when urea is used as a fertiliser and is eventually released back to atmosphere. Using urea as a chemical feedstock may result in more permanent storage of CO_2. There will be an associated cost of carbon with production, transport and application of urea as a fertiliser which will increase the amount of embedded CO_2 per tonne of urea used. Edge Environment Case Study Result: 2.27t CO_2-e/t reused. Case Study Description: Capture from a coal-fired power station in China, supplying a Urea Synthesis plant via a 9km pipeline.

ITEM	SPECIFIC SUB-CRITERION	SCORE	EVALUATION COMMENTS
4.03	Environmental Benefit (Non CO_2 abatement related)	0	No additional specific environmental benefits have been identified.
4.04	Social Benefit (Non CO_2 abatement related)	0	No specific social benefits have been identified.
Developing Countries			
5.01	Applicability to developing countries	2	Does not specifically favour developing countries.

TECHNOLOGY: ENHANCED GEOTHERMAL SYSTEMS (EGS)	DATE: 10/06/10

Technology Definition:

The use of supercritical CO_2 as a working fluid in a closed loop (is proposed in place of water) in Enhanced Geothermal Systems (EGS) to recover geothermal heat from hot dry rocks (HDR) kilometres underground, to bring heat to the surface and to generate power through a supercritical CO_2 turbine.

Proponents:

Joint venture of GreenFire Energy with Enhanced Oil Resources

Geodynamics Limited Innamincka 'Deeps' Joint Venture with Origin Energy.

ITEM	SPECIFIC SUB-CRITERION	SCORE	EVALUATION COMMENTS
Technology Maturity			
1.01	Timeframe to deployment	1	The technology is unlikely to be commercialised within the next 10 years as EGS itself (with the use of water as the working fluid) is a relatively novel technology. There are also a number of significant issues that need to be resolved to use CO_2 as the working fluid. These include: • the geochemistry of supercritical CO_2; • dealing with reservoir water; • long term effects in terms of reservoir connectivity; • the source of CO_2; • the long term retention of CO_2; and • design and optimisation of turbines and air-cooled heat exchanger systems to work with supercritical CO_2. Additionally, testing the use of supercritical CO_2 as the working fluid in geothermal systems is not projected to commence until 2013.
Scale-Up Potential			
2.01	Scale-up potential	2	Based on long term reservoir pressurisation/fluid loss studies – there is potential to continuously sequester 24 tonnes of CO_2 per day per MWe by fluid diffusion into the rock mass surrounding the HDR reservoir. e.g. For a 500MWe EGS there is potential to use and sequester 4.4Mt/year of CO_2. Scale-up potential will be dependent on available HDR sites. To achieve >300Mtpa CO_2 abated would require over 68 EGS sites each with 500MWe capacity. On this basis a score of 2 has been awarded.

ITEM	SPECIFIC SUB-CRITERION	SCORE	EVALUATION COMMENTS
2.02	Geographical constraints on the production system	1	Technology and production will be dictated by the location, accessibility and suitability of HDR/EGS. It is unlikely that a large source of CO_2 emissions will be in close proximity to an EGS, resulting in the requirement for long pipeline and compression stations, increasing project costs.
Value for Money			
3.01	Commercial viability	2	The technology is not likely to be commercially viable within the short-medium term. There are a number of factors which will impact the commercial viability of the project including: • High capital costs associated with the technology including construction of geothermal power plant, reservoir exploration, drilling and well stimulation costs. Average enhanced geothermal systems using water as the transmission fluids can include capital costs above $4 million per MW (compared to $3.5m per MW for standard geothermal projects). An average geothermal power plant is c.40–60 MW so capital costs of geothermal system are c.$160–$240m. The levelized costs above $0.054 per kWh in 2007. • High risk of large sunk costs in failed exploration for new sites (A typical well doublet in Nevada can support 4.5 megawatts (MW) of electricity generation and costs about $10 million to drill, with a 20 per cent failure rate). • Limited useful economic life of c.15-30 years (after this time it is expected that heat generation can fall to as low as 10 per cent). • Current low consumption of geothermal power (providing less than 1 per cent of current global energy consumption). • Uncertainty over supply being able to meet demand (e.g. cannot guarantee success of exploration attempts). • Inflexibility of technology to short term changes in demand (e.g. due to increases in crude oil prices). • Global deployment may be limited due to the availability of suitable sites. However, the global renewable energy market is expected to see dramatic growth in future with many countries incentivising the use of renewable sources and with world energy demand expected to increase by over 40 per cent in the next two decades there is significant potential.

ITEM	SPECIFIC SUB-CRITERION	SCORE	EVALUATION COMMENTS
3.02	Competitiveness with other technologies	1	The use of supercritical CO_2 as the transmission fluid in an Enhanced Geothermal System will compete with the traditional systems using water as the transmission fluid. The competitiveness of this technology will depend on a number of factors including: • the availability of a suitable CO_2 source; • the relative costs of capturing and transporting the CO_2 compared with water (This factor is likely to be dependent on where the technology is being implemented due to water being a more scarce and therefore valuable commodity in some regions); and • the quality of the site (e.g. how much heat can be extracted and for what period). Furthermore, the resulting power generated through the technology will need to be price competitive against the current alternative energy sources (both renewable and non-renewable) which is difficult to estimate in the long term given the volatility of crude oil and natural gas prices. Displacement of competitors is likely to be difficult in the short-medium term but likely to be aided by government incentives to support the use of renewable energy. However, this support cannot be relied upon to deliver actual economic feasibility of the technology.
3.03	Barriers / Incentives / Drivers	1	Over 60 countries have renewable energy targets. This coupled with the large forecast increase in total world energy consumption will contribute to the increased demand for renewable energy in the future. There is a large amount of government support internationally with the US, Australia, UK and other EU governments having all funded research into the technology. The commercial use of CO_2 as a transmission fluid is still in the early stages of R&D with the technical, commercial and economic feasibility still to be tested. The suitability of the reservoirs as a permanent CO_2 storage solution is uncertain. Although the technology seems to have strong political support it is likely to face a large amount of public opposition particularly if the reservoirs are to be used as permanent CO_2 storage solutions.

ITEM	SPECIFIC SUB-CRITERION	SCORE	EVALUATION COMMENTS
CO_2 Abatement Potential, Environmental and Social Benefits			
4.01	Permanence of Storage	3	The process will leave significant volumes of CO_2 sequestered underground, (geological storage). However long term permanence, (leakage) and MMV will be key issues.
4.02	Additional CO_2 emissions from reuse	2	The CO_2 balance depends largely on the location of the CO_2 supply. The CO_2 emissions intensity will increase based on the distance of the CO_2 supply pipeline, due to increased compression requirements. Based on a 500MW EGS, with 500tonne/hr of CO_2 sequestered and assuming that 100MW is required for capture, compression and transport of the CO_2 emission source, emissions of CO_2 per tonne of CO_2 reused is <0.5t/hr. Edge Environment Case Study Result: 0.58t CO_2-e/t reused. Case Study Description: Capture from coal-fired power stations in SE QLD, Australia, delivered via a 970km pipeline to the Cooper Basin, Australia.
4.03	Environmental Benefit (Non CO_2 abatement related)	0	No additional specific environmental benefits, although CO_2 will replace the use of water.
4.04	Social Benefit (Non CO_2 abatement related)	0	No specific social benefits have been identified.
Developing Countries			
5.01	Applicability to developing countries	2	This technology is equally applicable to developing and developed countries (provided there is a HDR source and a suitable point source of CO_2.

Notes: The use of supercritical CO_2 as the working fluid for EGS is likely to advance the deployment of CCS (carbon capture and geological storage), as it requires the key components of the CCS train. However the technology is unlikely to be available in the next 10 years, and hence does not drive the need for CCS in the short term.

TECHNOLOGY: CO_2 FEEDSTOCK FOR POLYMERS	DATE: 11/06/10

Technology Definition:

CO_2 is used as a feedstock to synthesise polymers and high value chemicals. The technology transforms waste carbon dioxide into polycarbonates using a proprietary zinc based catalyst system, which reacts CO_2 and traditional polymer feedstocks to create polypropylene carbonate (PPC) and polyethylene carbonate (PEC). Polymers contain up to 50 per cent CO_2 by mass.

Proponents:

Novomer Ltd is under taking demonstration scale CO_2 polycarbonate production at a Kodak Speciality Chemicals facility. Novomer uses a proprietary catalyst developed by Cornell University in this process and have partnered with Praxair Ltd to supply the required repurposed CO_2.

ITEM	SPECIFIC SUB-CRITERION	SCORE	EVALUATION COMMENTS
Technology Maturity			
1.01	Timeframe to deployment	2	Novomer Ltd is producing CO_2 feedstock polycarbonates on a pilot scale at Kodak Speciality Chemicals facility in Rochester, NY, and has been since December 2009. To date, Novomer have demonstrated the process in a 1,500 litre batch reactor and are investigating processing polymers using a continuous flow reactor to improve production cost. Simultaneously, the polymers are being tested in a range of conversion processes that include thin film extrusion to blow moulding. Materials produced are being offered to potential customers for testing. In March 2010, Novomer partnered with Praxair to supply the required repurposed CO_2 and Kodak Specialty Chemicals, a unit of Eastman Kodak to support polymer process development and scale-up. At the end of the project, in addition to enabling commercial-scale manufacturing capabilities from sustainable materials with several contract manufacturers, it is expected that several products will be customer qualified requiring commercial scale production of PPC polymers on a global basis. Given Novomer's level development is at demonstration stage, producing a product which potential customers are testing and scale-up production is supported by Kodak Speciality Chemicals (processing unit) and Praxair (CO_2 supply), it is expected Novomer could achieve commercial-scale manufacture of PPC polymers for supply to customers who have qualified the product.

ITEM	SPECIFIC SUB-CRITERION	SCORE	EVALUATION COMMENTS
Scale-Up Potential			
2.01	Scale-up potential	2	In the current global plastic market, polyethylene (PE) production in 2007 reached approximately 80Mt[12] and polypropylene (PP) production totalled 45Mt[13], representing the two largest polymer markets. The attributes which provide these thermoplastics with market dominance include stiffness, impact resistance, barrier protection, and suitability to all common manufacturing processes, allowing for a wide range of uses, particularly in food and general packaging applications. Novomer's polycarbonate polymers aim to be used in similar applications as PE and PP. Based on Novomer figures from their proprietary catalyst, it is estimated polymers contain up to 50 per cent CO_2 by mass. To compete against PE and PP's dominance in the market and in turn scale up, PPC will have to compete on a cost basis to win market share. Packaging, which thermoplastics are widely used, is a low end application so demand will be largely driven by the lowest cost polymer which has suitable properties to fulfil an application. CO_2 as a feedstock is widely available from a point sources (e.g. syngas production, natural gas sweetening, coal power production), which will require capture, compression and potentially an additional processing step to increase the degree of purification. This will create significant capital cost, however is balanced by a low operating cost when CO_2 feedstock is compared to petroleum derived feedstocks. Considering the global thermoplastic production levels listed above, if PPC can compete with this market on cost, the potential for scale-up is significant. Assuming a conservative 4 per cent annual growth on existing PE / PP markets over the next 5 years, and assuming a displacement of 40 per cent of the PE and PP market would see over 30mt CO_2 used as feedstock. The price volatility of finite petroleum feedstocks could also lead to increased use of CO_2 feedstock polycarbonates and scale-up potential.

12 Piringer & Baner 2008, p.32
13 http://www.ceresana.com/en/market-studies/plastics/polypropylene/

ITEM	SPECIFIC SUB-CRITERION	SCORE	EVALUATION COMMENTS
2.02	Geographical constraints on the production system	3	Geographical constraints are limited as existing chemical industry infrastructure (e.g. polymer plants) could be used to manufacture CO_2 feedstock plastic. Proximity to a CO_2 source is also required which as polymer plants are generally connected to refineries and gas plants to receive petroleum feedstocks, CO_2 could also be readily available at the point of manufacture. In developing countries lacking existing infrastructure, a commercial scale plant could be built next to a CO_2 point source (e.g. power, fertiliser, cement plant) to reduce the need for feedstock transport. Transportation emissions of polymer product would also be reduced, along with its final cost.
Value for Money			
3.01	Commercial viability	2	The research and development undertaken by Novomer suggests that, in theory, this technology can become commercially viable. However, given that all of the research has been conducted by a single company, claims and statements made by Novomer may be biased or unrepresentative of the technology as a whole. Although a number of the polymer prototypes have been provided to potential customers for testing, as yet none have been accepted in the market. The outcome of such testing may have a major impact on the commercial viability of the technology. There is a global demand for polymers and so the technology has the potential for wide reaching commercialisation. Novomer claim that the technology can be used in existing commercial plants. However, there is a lack of information as to the costs associated with this or the advantages to the manufacturer of implementing such technology. The lack of reliable information and demonstration projects means that commercial and economic feasibility are uncertain.

ITEM	SPECIFIC SUB-CRITERION	SCORE	EVALUATION COMMENTS
3.02	Competitiveness with other emerging technologies	2	Novomer claim that the polycarbonate polymers can be used as an alternative to existing petroleum based polymers in numerous applications, but the suitability of these products to the intended applications has yet to be verified. Based on the information available, there are no indications that the polycarbonate polymers will be superior to the existing alternatives available. Given that the polymer market is largely driven by high volume and low value products, the ability for the entry of these products into the market will almost certainly be solely driven by their price competitiveness. Novomer claim that the products could be price-competitiveness with existing products, even without a carbon capture scheme, however there is no evidence on the costs associated with the demonstration project or anticipated costs on a commercial scale to support this statement.
3.03	Barriers / Incentives / Drivers	2	The main barriers for this technology include: • Uncertainty over suitability of polycarbonate products for existing polymer applications; • Lack of demonstration projects to assess economic feasibility; and • Difficulties of entering market. Novomer has raised about $21 million of funding to date with private funding from OVP Venture Partner, Physic Venture Partners, Flagship Ventures and DSM Venturing and nearly $2 million in grants from the U.S. Department of Energy (DOE), the National Science Foundation and the state of New York. Volatility of petroleum prices may drive manufacturers to use technology to provide more long term certainty over costs.

ITEM	SPECIFIC SUB-CRITERION	SCORE	EVALUATION COMMENTS
CO_2 Abatement Potential, Environmental and Social Benefits			
4.01	Permanence of Storage	2	CO_2 based polymers could be used for a range of applications, including packaging (e.g. plastic bags, bottles and film wrap), EOR surfactants, automotive and medical components and protective coatings for wood and metal. In pure form, CO_2 polymers are aliphatic polycarbonates (compounds in which carbon atoms are linked in open chains), which bacteria can attack and break down. Degradation could occur in as short as 6 months under the right compost conditions. CO_2 will be released back into the atmosphere in this case making CO_2 storage non-permanent. While not assisting long term CO_2 storage, this is a desirable property for packaging which is often redundant after single use, creating a large waste burden (and CO_2 load through transport and disposal), as traditional polymers can take hundreds of years to break down and if not economic to recycle, are sent to landfill. Other applications such as EOR surfactants, medical and automotive components can use additives to prevent degradation or will not be in a microbe environment so storage will be permanent. The size of these applications will be less than packaging use.
4.02	Additional CO_2 emissions from reuse	2	Public domain details on the energy demands of CO_2 feedstock polymerisation are not quantified by Novomer. Their proprietary catalyst reacts CO_2 and epoxide molecules via a low energy pathway, reportedly making the process economical through reducing the energy required to drive the reaction. Energy inputs to the process (additional requirements above baseline operations) are minimal and hence a score of two has been awarded. Edge Environment Case Study Result: 5.5t CO_2-e/t reused. Case Study Description: Capture from a coal-fired power station in the USA, delivered via a 9km pipeline to the polypropylene carbonate production facility.

ITEM	SPECIFIC SUB-CRITERION	SCORE	EVALUATION COMMENTS
4.03	Environmental Benefit (Non CO_2 abatement related)	0	An environmental benefit could be provided through CO_2 polymers biodegradability. While not assisting long term CO_2 storage, this is a desirable property for packaging which is often redundant after a single use, creating a large waste burden (and CO_2 load through transport and disposal). Traditional polymers can take hundreds of years to break down and if not economic to recycle, are sent to landfill. However, widespread use of CO_2 based plastics would require large scale compost infrastructure to successfully biodegrade and dispose of, which is not established so will not be considered a benefit.
4.04	Social Benefit (Non CO_2 abatement related)	1	The use of thermoplastics is falling due to a concerted effort, particularly in the Western world where use is greatest, to reduce packaging and waste, such as plastic bags. Being environmentally beneficial in capturing CO_2 could provide consumer support through green marketing. At a time when CCS is struggling for public acceptance, particularly when low-carbon energy will mean increased power bills, consumers have shown a willingness to pay a small price for plastic bags and find alternatives such as reusable bags. Carbon capture in items such as plastic bags and food packaging, which are used regularly could make the issue of carbon abatement more relevant and practical to help public acceptance.
Developing Countries			
5.01	Applicability to developing countries	2	This technology is applicable to both developing and developed countries. Developing countries investing in manufacture could build a commercial scale plant next to a CO_2 point source to reduce the need for feedstock transport. This comes with a high capital cost however, so it is assumed (if the technology becomes commercial) existing polymer processing infrastructure will be used in the short term.

TECHNOLOGY: CO_2 ABSORPTION BY MICROALGAE TO GENERATE BIOMASS.	DATE: 22/06/10

Technology Definition:

Bubbling CO_2 through algal cultivation systems can greatly increase production yields of algae. There has been significant interest in the last few decades in the potential of algae to produce vast quantities of oil at a price that is competitive with crude oil.

Proponents:

Many companies and research institutes globally (reportedly 200 or more ventures exist). Several large global companies including BP, ExxonMobil, Chevron, Connoco Philips, Virgin Fuels, Anglo Coal and Royal Dutch Shell all have sizeable research interests.

ITEM	SPECIFIC SUB-CRITERION	SCORE	EVALUATION COMMENTS
Technology Maturity			
1.01	Timeframe to deployment	2	Although large-scale open systems do exist the use of CO_2 to enhance growth is not common practice with the majority of systems operating today which typically produce high value nutraceuticals rather than energy products (e.g. transport fuel). There are many technological and operational issues to be addressed before a robust large scale system can produce oil at a price competitive with crude oil. Despite claims of some firms, most proponents of the technology agree that there is great potential but the technology is 5-10 years away from commercial realisation.
Scale-Up Potential			
2.01	Scale-up potential	2	Where algal oil is used as a feedstock for biodiesel production, the potential market is very large. The market for other products of algae (e.g. algal meal) may not be as large, though algal meal could also be further processed into commodity products such as char. Algenol currently propose a project in Mexico capturing and reusing 1.5Mtpa CO_2, which would demonstrate the concept on a large scale on a single site. It remains to be seen whether this project will be fully implemented.
2.02	Geographical constraints on the production system	2	The amount of CO_2 which can be captured from a point source will be constrained by the land available on a case by case basis. Systems are ideally suited to locations with high solar irradiance and adequate marginal land. Access to a water source is also desirable. Products can be readily transported using existing methods and infrastructure.

ITEM	SPECIFIC SUB-CRITERION	SCORE	EVALUATION COMMENTS
Value for Money			
3.01	Commercial viability	2	The use of recycled CO_2 for algae cultivation is still in the early research and development stages. There are currently no large scale algae cultivation projects in operation to support the potential economic and commercial feasibility of the technology. The likely use of the algae would be for the large scale production of biomass fuel which has a large potential market. 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.[14] Algae farms require a large amount of suitable land and ideally these would be located close by the CO_2 source. Some initial research done at universities and during pilot projects suggest that it could take an open pond of about 8 square miles (5120 acre pond) to produce enough algae to remove carbon dioxide from a midsized – 500 MW – power plant.[15] This high land requirement may limit the commercial viability of the technology in areas with high land prices.

14 Biofuels 2010: Spotting the Next Wave; Joshua Kagan The Promoteus Institute | Travis Bradford The Prometheus Institute (December 2009)

15 Algae based CCS, CO_2 Carbon Capture Algae biosequestration – Power Plant CCS. http://www.powerplantccs.com/ccs/cap/fut/alg/alg.html

ITEM	SPECIFIC SUB-CRITERION	SCORE	EVALUATION COMMENTS
3.02	Competitiveness with other emerging technologies	1	Algae biofuel would need to compete with alternative biofuels such as those derived from food feedstock (e.g. rapeseed oil, soyabean oil and hemp) as well as those derived from vegetable and animal fats. However, given the biofuel forecasts stated in 3.01 there is significant potential for algae biofuel to enter the market. Furthermore, algae biofuel may be a suitable alternative to those using feedstock as it will not be affected by the relative demand of the feedstock as a food source as it does not use these often valuable crops as feedstock. However, the relative costs of production of these biofuels will be the key driver. On a wider scale algae biofuel will have to compete with current fuel sources (e.g. petroleum) if it is to be considered as a commercial alternative for use as a transport fuel. Again, the determining feature of its success will be its price competitiveness in the market. At its current stage of development the technology is expensive (the current cost of producing algae for carbon sequestration in BC (British Columbia) is $793 per tonne of CO_2). At present the cost of producing the end product (biomass fuel) is very high in comparison to existing products (Assuming that algal biomass had content of 25 per cent oil, then the estimated cost of production would be $20,000/tonne of oil, or over 20-fold higher than current vegetable or crude oil prices).[16] At present it appears unlikely that algae biofuel will be able to compete with alternative products in the current market.

16 OPPORTUNITIES AND CHALLENGESIN ALGAE BIOFUELS PRODUCTION; A Position Paper by Dr. John R. Benemann in line with Algae World 2008

ITEM	SPECIFIC SUB-CRITERION	SCORE	EVALUATION COMMENTS
3.03	Barriers / Incentives / Drivers	1	There are a number of barriers which will affect the value for money and commercialism of this technology including: • The use the technology is most suited to regions with high solar resource and large areas of marginal land surrounding point CO_2 sources (providing the most productive environment for algae cultivation) which will inhibit the implementation of the technology in many regions. • Algae farms are large and appropriate land large enough to accommodate technology for the CO_2 generation of a power plant will be difficult to source and expensive (Estimated capital cost of algal farm per hectare is: $138,000 with operating costs of $43,800 pa).[17] • At the current stage of development the technology is expensive (the current cost of producing algae for carbon sequestration in BC (British Columbia) is $793 per tonne of CO_2).[18] • The cost of producing the end product (biomass fuel) is very high in comparison to existing alternative fuel sources. • Current studies assume that the algae production takes place at the site of the CO_2 source (with CCS costs of c.$40 tonne) and so additional transport and storage costs will need to be accounted for.[19] The research into the technology has attracted both public funding from Department of Energy and Department for Transport in the UK and funding from a number of private investors.

17 GREENHOUSE GAS SEQUESTRATION BY ALGAE – ENERGY AND GREENHOUSE GAS LIFE CYCLE STUDIES; Peter K. Campbell, Tom Beer, David Batten

18 Microalgae technologies and processes for biofuels/bioenergy production in British Columbia; The Seed Science Ltd (January 2009)

19 OPPORTUNITIES AND CHALLENGES IN ALGAE BIOFUELS PRODUCTION; A Position Paper by Dr. John R. Benemann in line with Algae World 2008

ITEM	SPECIFIC SUB-CRITERION	SCORE	EVALUATION COMMENTS
CO_2 Abatement Potential, Environmental and Social Benefits			
4.01	Permanence of Storage	2	CO_2 which is absorbed by algae is used to generate biomass. Dependant on the system there may be a mixture of end products produced from this. A basic system may generate only biodiesel in this case the storage is temporary as the CO_2 is re-released when the fuel is burnt. Another system may generate biodiesel, supply crude algal oil for processing to plastics, useful nutraceuticals may be extracted and used in food supplements, the algal biomass remaining after extraction may then go on to produce animal feed, fertiliser, or biochar, or be digested anaerobically to produce biogas. Some of these avenues will result in permanent storage. The second 'biorefinery' option is more desirable as risk is spread across several supply chains.
4.02	Lifecycle CO_2 analysis	3	The production of algae consumes CO_2 at the rate of 1.8 tonnes of CO_2 for every tonne of algal biomass produced. However is likely the majority of this CO_2 will be re-released. There will also be some CO_2 produced during cultivation due to the power requirement of pumping large volumes of water as well as CO_2 production from any downstream processing operations. Edge Environment Case Study Result: 0.41t CO_2-e/t reused. Case Study Description: Algae farm integrated with a coal-fired power station in Eastern Australia, with process requirements similar to those identified in public documents of MBD Energy.
4.03	Environmental Benefit (Non CO_2 abatement related)	1	Algae cultivation systems can be used as a step in waste water treatment – to remove certain compounds from waste water/sewage.
4.04	Social Benefit (Non CO_2 abatement related)	1	Algae systems which are constructed on marginal land and used to produce biofuels would not compete with food crops for arable land. The use of algal biofuels avoids the current food vs. fuel problems surrounding first generation soy/palm/corn/wheat/canola biofuels.
Developing Countries			
5.01	Applicability to developing countries	2	Does not specifically favour developing countries. Solar irradiance and available marginal land are the main factors which will constrain the development of such systems.

TECHNOLOGY: MINERALISATION	DATE: 10/06/10

Technology Definition:

Carbon mineralisation is the conversion of CO_2 to solid inorganic carbonates using chemical reactions.

Proponents:

CMAP technology – Carbon Mineralisation by Aqueous Precipitation is being commercialised by Calera

Skymine technology is being commercialised by Skyonic Corporation.

ITEM	SPECIFIC SUB-CRITERION	SCORE	EVALUATION COMMENTS
Technology Maturity			
1.01	Timeframe to deployment	3	The technology is likely to become commercial in ≤5 years based on the following information: The Calera Yallourn project based in the Latrobe Valley in the state of Victoria, Australia is expected to start construction of a demonstration plant during 2010. The plant will be expanded to commercial scale following the initial demonstration phase. Phase 1 of Capitol-SkyMine demonstration facility has been initiated at Capitol Aggregates, Ltd cement plant in San Antonio, Texas, USA. (This includes modelling, simulation, design, costing, and procurement activities). Construction of a commercial-scale facility is anticipated by the third quarter of 2010.
Scale-Up Potential			
2.01	Scale-up potential	3	According to Calera, the current global demand for building materials is currently estimated at 32 billion tonnes per year. Addressing this market would require more than four thousand 500 MW Calera plants. Since every tonne of Calera's cements and aggregate contain about half a tonne of sequestered carbon dioxide, the markets for Calera's solid products would constitute a very significant consumption of CO_2, e.g. 16 billion tonnes per year. In summary, the scale-up potential for Calera's technology is significant.

ITEM	SPECIFIC SUB-CRITERION	SCORE	EVALUATION COMMENTS
2.02	Geographical constraints on the production system	2	Production is possible anywhere in proximity to a CO_2 source and an abundant supply of brine and flyash. The maximum scale of the technology is restricted by the available resources of brine and flyash to provide the requisite hardness and alkalinity required and within abundant supply. If brine source is not suitable or abundant in supply then the technology requires manufactured alkalinity. Calera has developed a proprietary technology for manufacturing alkalinity – alkalinity based on low energy manufacturing process (ABLE) which is reported to be approximately 40 per cent less energy intensive then conventional manufacturing methods. Due to the volume of products produced transportation requirements are likely to be extensive and therefore relatively expensive.
Value for Money			
3.01	Commercial viability	3	Large scale commercialisation is viable in the short-medium term with construction on Calera's first commercial scale project, the Calera Yallourn project is based in the Latrobe Valley in the state of Victoria, due to commence this year. The Yallourn project will begin with a demonstration phase where it will be operated on a scale (with a carbon capture capacity of 50MW) before entering the commercial phase (with a carbon capacity of 200MW). Both the CMAP and Skymine technologies are in the process of being commercialised by Calera and Skyonic Corporation. Based on research and development by Calera and Skyonic, the technology is highly likely to be commercially and economically viable without the need for a carbon price or similar incentive. Global implementation of this technology is possible since resulting inorganic carbonates are currently produced and used worldwide.

ITEM	SPECIFIC SUB-CRITERION	SCORE	EVALUATION COMMENTS
3.02	Competitiveness with other technologies	2	The current global demand for building materials is estimated at 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. Based on current research and development, Calera claim that CMAP 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. Calera claim that CMAP technology can be implemented in existing cement production facilities which may aid entry and growth within the market. Initial market entry may be hampered by potential public perception of the products being inferior to existing alternatives and for the method to be accepted and approved by regulators (Note that it took Portland Cement Association about 25 years to get the standards changed to allow 5 per cent limestone in the Portland cement mix).
3.03	Barriers / Incentives / Drivers	2	Requires co-location of CO_2 source. However flue gas produced from cement production facilities is itself a suitable source. Therefore the CMAP technology could be implemented on site quite straightforwardly. Capital costs of $1,500–$1,900 per MW of CO_2 capture, based on 200MW Calera Latrobe Valley plant which has an estimated total capital investment for carbon capture of $300–$380m, may limit implementation by existing manufacturers (although may be mitigated in presence of an emissions trading scheme).
CO_2 Abatement Potential, Environmental and Social Benefits			
4.01	Permanence of Storage	3	The mineral carbonation process presents permanent sequestration of CO_2 for centuries in the form of fine or coarse aggregates or supplementary cementitious material (SCM), which can be used as building materials, construction of roads, etc.

ITEM	SPECIFIC SUB-CRITERION	SCORE	EVALUATION COMMENTS
4.02	Additional CO_2 emissions from reuse	3	The CO_2 balance depends largely on the source of alkalinity. The CO_2 emissions intensity will increase if the ABLE technology is required to manufacture alkalinity. Figures of 0.5 to 1.2MWh/t CO_2 have been indicated as the energy input needed for electrolysis in the Calera's proprietary ABLE technology. Additionally, there are potentially large transportation impacts depending on the production and user locations. For example, each tonne of building materials shipped from Yallourn to China (over 8,500km) generates 0.12 tonnes CO_2 equivalent. Because of the uncertainty of the availability of suitable brine resource and the unknowns with the ABLE technology, a moderate score is awarded. Edge Environment Case Study Result: 0.32t CO_2-e/t reused. Case Study Description: PB Estimate of requirements based on capture at a brown-coal fired power plant in Victoria, Australia, with no requirement for manufactured alkalinity.
4.03	Environmental Benefit (Non CO_2 abatement related)	1	Calera's process has the potential to avoid the environmental destruction from mining and the heavy transportation carbon footprint associated with the 32 billion tonnes of mined aggregate sold every year, which is larger than coal. The technology has the capability to reuse fly ash in the process which in the future may be considered and designated as a hazardous material requiring regulated storage.
4.04	Social Benefit (Non CO_2 abatement related)	1	One of the by products is fresh water that could be used as potable water, irrigation water, or an industrial water supply, which may alleviate the water deficit in some regions, benefiting society in the region.

ITEM	SPECIFIC SUB-CRITERION	SCORE	EVALUATION COMMENTS
Developing Countries			
5.01	Applicability to developing countries	3	This technology is applicable to both developing and developed countries (provided there is a concentrated CO_2 source, flyash, brine source available), and that there is a market for aggregate/construction materials. However technology may be more applicable towards developing countries, e.g. China has shown particular interest in this technology. If the Calera CMAP process were to be used in conjunction with a desalination plant there is also potential for significant cost and energy savings.

Notes: The Calera technology will not advance the deployment of CCS (carbon capture and geological storage), as it does not require any key components of the traditional CCS train. The process takes untreated flue gas from a point source emission such as power plant, without the need for CO_2 to be separated or purified from the waste stream.

TECHNOLOGY: CONCRETE CURING	DATE: 21/06/10

Technology Definition:

Point source emission of CO_2 used to limit the need for heat and steam in the curing process in the production of precast concrete products.

Proponents:

Carbon Sense Solutions Inc. (CSS)

ITEM	SPECIFIC SUB-CRITERION	SCORE	EVALUATION COMMENTS
Technology Maturity			
1.01	Timeframe to deployment	3	The technology is likely to become commercial in ≤5 years based on plans for a demonstration plant in 2011 and commercialisation in 2012.
Scale-Up Potential			
2.01	Scale-up potential	2	According to CSS, the US demand for precast concrete makes up about 12 per cent of the US concrete market. Every tonne of precast concrete contains approximately one twelfth of sequestered carbon dioxide. Based on 5 billion tonnes of concrete used globally per annum, and an estimated 10 per cent is pre-cast concrete, there is potential for 60Mtpa of CO_2 to be sequestered by concrete curing.
2.02	Geographical constraints on the production system	1	The reuse of CO_2 for concrete curing can only occur at precast concrete plants. Generally onsite flue gas emissions will be used, and/or from local/ neighbouring combustion sources.
Value for Money			
3.01	Commercial viability	2	The technology is commercially viable since concrete curing, via a moist, controlled environment, is an established practice required to strengthen and harden precast concrete. The use of CO_2 in the curing process has been shown to be technically effective and the suitability of the CO_2 sourced from the concrete producers' own flue gas will aid the economic feasibility through lower CO_2 capture and transport costs. With approximately 5 per cent of all CO_2 emissions[20] coming from concrete production a system of carbon credits or a carbon tax may provide an incentive for concrete producers to consider using carbon dioxide as a curing agent.

20 Recycling carbon dioxide into concrete: a feasibility study; Y. Shao, S. Monkman and A. J. Boyd

ITEM	SPECIFIC SUB-CRITERION	SCORE	EVALUATION COMMENTS
3.02	Competitiveness with other emerging technologies	2	The technology will need to compete with existing curing technologies of using carefully controlled moisture and temperature environments without high CO_2 contents. Some studies have shown that the use of CO_2 accelerates the strength and reduces the curing time required which may incentivise producers to adopt the use of the technology. The ability to use the flue gas produced from the concrete producer itself will increase demand for the technology over existing alternatives in areas where there exists a carbon scheme. Concrete cured using this technology is unlikely to be able to be sold at a premium over existing products and therefore its competitiveness will be determined by the costs that can be saved (through reduced curing times, carbon tax etc.) in using this technology over traditional methods.
3.03	Barriers / Incentives / Drivers	2	The main value for money barriers of this technology is the limitation of its use to existing concrete producers due to the requirement for it to be implemented at the precast concrete plants. The main drivers and incentives for the commercialisation of the technology are: • the potential to reduce curing times of concrete; and • the ability to capitalise on any applicable carbon schemes.
CO_2 Abatement Potential, Environmental and Social Benefits			
4.01	Permanence of Storage	3	The mineral carbonation and curing process presents permanent sequestration of CO_2 for centuries in the form of precast concrete products.
4.02	Additional CO_2 emissions from reuse	1	Limited information available, however, energy inputs to the precast concrete manufacturing process (additional requirements above baseline precast operations) are minimal. Ambient conditions required for reuse of captured flue gases. Edge Environment Case Study Result: 2.20t CO_2-e/t reused. Case Study Description: Utilises a flue gas slipstream from a coal-fired power station in Nova Scotia, Canada, with the precast facility located in close proximity.

ITEM	SPECIFIC SUB-CRITERION	SCORE	EVALUATION COMMENTS
4.03	Environmental Benefit (Non CO_2 abatement related)	0	No specific environmental benefits have been identified.
4.04	Social Benefit (Non CO_2 abatement related)	0	No specific social benefits have been identified.
Developing Countries			
5.01	Applicability to developing countries	3	This technology is applicable to both developing and developed countries, however is likely to be biased towards developing countries due to the increased construction required for development.

TECHNOLOGY: BAUXITE RESIDUE CARBONATION	DATE: 11/06/10

Technology Definition:

Residue carbonation is the addition of gaseous CO_2 to the thickened residue slurry, prior to the deposition of this slurry onto the residue drying areas. The CO_2 reacts with the alkaline components within the liquor, and if held in contact with the slurry for long enough, the adsorbed and solid forms of alkalinity are also reacted.

Proponents:

Alcoa of Australia

CSIRO

ITEM	SPECIFIC SUB-CRITERION	SCORE	EVALUATION COMMENTS
Technology Maturity			
1.01	Timeframe to deployment	3	Alcoa of Australia operates this process commercially at their Kwinana Alumina refinery, utilising a concentrated stream of CO_2 from CSBP's Ammonia Plant. Alcoa's patents on the technology have expired, but they are offering other alumina producers a 'technology transfer' package that includes their more detailed intellectual property.

ITEM	SPECIFIC SUB-CRITERION	SCORE	EVALUATION COMMENTS
Scale-Up Potential			
2.01	Scale-up potential	1	Alcoa's process at present requires only 30-35kg CO_2/tonne red mud (dry weight), which applied to the current total global production represents a maximum CO_2 consumption of 2.45Mtpa. This technology was retained for more detailed investigation on the basis of the large theoretical capacity of red mud treated with sea water to absorb CO_2 (up to 750kg CO_2 / t red mud). However, Alcoa advise the following: 'We have only proposed a level of 30-35kg per tonne of red mud (dry weight) as this is what is required to convert all of the alkalinity to carbonates. We can push this further to produce bicarbonates, but the long term equilibrium is a carbonate, so there will always be questions around whether you can retain the extra bicarbonate CO_2 within the residue. This is in our "to-do" list for the future.' Given that high CO_2 addition rates could only be justified if the addition was considered storage under an emissions trading scheme, scale-up potential is considered limited.
2.02	Geographical constraints on the production system	2	The technology requires that a concentrated and preferably high pressure source of CO_2 be located in reasonable proximity to an alumina refinery. (Refer to Alcoa's comments in 3.01 below, stating an 85 per cent CO_2 purity. Furthermore, Alcoa patent documents suggest the process may be designed to operate at 4MPa, which would clearly favour high pressure sources of CO_2 (to eliminate or minimise gas compression costs). Without undertaking a detailed analysis of alumina refinery locations relative to industrial sources of CO_2, it is reasonable to expect that this will be a constraint for some refinery locations.

ITEM	SPECIFIC SUB-CRITERION	SCORE	EVALUATION COMMENTS
Value for Money			
3.01	Commercial viability	2	More than 70 million tonnes of bauxite residue is generated annually through the manufacture of aluminium. Residue carbonation has been proven to be commercially viable by Alcoa. However the technology of further carbonation to produce bicarbonates (and sequester higher amounts of CO_2) has not yet been tested on a commercial scale and cannot be considered commercially viable. A potential benefit is the use of the neutralised residue as a soil amendment. Based on the Alkaloam® Sustainability Assessment , the residue would be available essentially free from Alcoa, though the farmers would still bear the cost of carting and field application of the Alkaloam (which can be initially estimated in the region of AU$14/t to AU$16/t Alkaloam). The main benefit to Alcoa would be in the form of a residue storage cost saving equivalent to ~AU$26/t CO_2. However this is sole dependent on the commercial acceptance of the use of Alkaloam as a soil amendment. Secondly, if used to neutralise acidic soils, there needs to be certainty that CO_2 will not be liberated from the carbonates and therefore returned to the atmosphere and further investigation into this area will be required before it can become commercially viable. The use of the current technology is also limited due to the current requirement of the CO_2 source to be located in close proximity to the alumina plant and so the global commercial viability of the use of recycled CO_2 is questionable. This is further affected by the need for relatively high CO_2 purity of 85 per cent compared to concentrations from power plants being significantly lower (c.10 per cent) and hence the requirement for a concentration process which would be highly costly. Alcoa's current commercial plant uses CO_2 produced from a local ammonia plant which provides a high purity source. PB estimate that for the Kwinana site, although the validity of which are limited by the availability of public information, the incremental cost of the carbonation operation (8km CO_2 pipeline plus carbonation plant), including capital, operating and maintenance costs, is probably less than AU$10/t CO_2 equivalent which suggests that large scale commercialisation of the technology is likely to be economically feasible.

ITEM	SPECIFIC SUB-CRITERION	SCORE	EVALUATION COMMENTS
3.02	Competitiveness with other emerging technologies	2	The resulting product is not a useful product in itself and therefore will not compete with any existing products in the market. The sole use for bauxite carbonation using CO_2 is to reduce its alkalinity from a pH of c.13.5 per cent to c.10.5 per cent. The advantages of a reduced pH are that the resulting bauxite residue is less toxic and potentially cheaper to handle and store. The process of bauxite neutralisation can also be achieved using seawater. This is an established technology currently being used at Queensland Alumina (QAL) in Queensland and Euralumina in Sardinia. The competitiveness of CO_2 neutralisation over seawater neutralisation will largely be dependent on location. For example the use of seawater neutralisation is likely to be the cheaper alternative in areas where seawater can be easily and cheaply sourced (e.g. near coastlines). However, CO_2 is likely to be more competitive in locations which are not located close by to a large seawater source. Therefore it is likely that the competitiveness of the two options in any given region will be largely dependent on the relative capture and transport costs of CO_2 and seawater to the aluminium manufacturing facility. In order for this technology to be competitive with existing practices (to permanently store high alkaline residue) the cost of carrying out the technology will need to be lower than the costs saved in handling, transporting and storing the end residue. There is insufficient information available to assess the economic feasibility of the widespread use of the technology through comparison of the associated costs. However, this is likely to be affected by a number of factors including: location of a suitable CO_2 source, costs required for CO_2 concentration, scale of aluminium plant, regional costs of bauxite handling, transportation and storage.
3.03	Barriers / Incentives / Drivers	1	There are a number of barriers which will affect the value for money of widespread implementation of the technology including: • high purity of CO_2 required; • locality of CO_2 source; • no prospects for revenues as a result of production of useful by-product; • relatively low levels of CO_2 sequestration; and • technology has not received any government funding/grants.

ITEM	SPECIFIC SUB-CRITERION	SCORE	EVALUATION COMMENTS
CO_2 Abatement Potential, Environmental and Social Benefits			
4.01	Permanence of Storage	2	Storage of carbon in the form of a mineral carbonate is thermodynamically favoured, and is highly likely to qualify as permanent storage under an emissions trading scheme. The IPCC views it as a highly verifiable form of permanent storage. Bicarbonates are not as thermodynamically favourable, and Alcoa has suggested there may be questions over the permanence of storage as bicarbonates. Storage as bicarbonates is not considered here. It is acknowledged that in the presence of a strong acid, carbonates will dissolve and release carbon dioxide. If Alkaloam is applied to acidic soils as a soil amendment, some CO_2 may be liberated – this issue may need further investigation.
4.02	Additional CO_2 emissions from reuse	1	Energy inputs to the carbonation process (additional requirements above baseline Alumina refinery operations) are minimal, with the residue carbonation process having a resultant emissions intensity probably ~0.02t CO_2 per tonne CO_2 used, assuming a typical Australian grid power supply and the CO_2 developed incidentally as a by-product of ammonia production (this does not consider possible CO_2 emissions reductions due to the flow-on benefits of residue carbonation). If a coal-fired power station were the source of CO_2 and power, the emissions of CO_2 per tonne of CO_2 used would be ~0.1t/t. Edge Environment Case Study Result: 0.53t CO_2-e/t reused. Case Study Description: Capture from a coal-fired power station in Western Australia, supplying the Kwinana Alumina Refinery via a 9km pipeline.
4.03	Environmental Benefit (Non CO_2 abatement related)	2	Reduced dusting potential of red mud; Potential for use of the carbonated red mud as a soil amendment for acidic soils (see also Bauxite Residue (Alkaloam®) Sustainability Assessment: Technical, Community Consultation, Benefit-Cost and Risk Assessment, published by the Centre for Sustainable Resource Processing – http://www.csrp.com.au/projects/alkaloam.html).
4.04	Social Benefit (Non CO_2 abatement related)	1	No specific social benefits have been identified.

ITEM	SPECIFIC SUB-CRITERION	SCORE	EVALUATION COMMENTS
Developing Countries			
5.01	Applicability to developing countries	0	Based on data from the International Aluminium Institute (http://stats.world-aluminium.org/iai/stats_new/formServer.asp?form=5), and the US geological survey (http://minerals.usgs.gov/minerals/pubs/commodity/bauxite/index.html#mcs) production of alumina is in the greater part (~65 per cent) in emerging and developing economies, with China the largest Alumina producer, and evidence of strong growth in Chinese production over the last 5 years (averaging approximately 28 per cent per annum).

TECHNOLOGY: RENEWABLE METHANOL	DATE: 10/06/10

Technology Definition:

Electrolysis of water to produce H_2. Catalysed reaction of H_2 and CO_2 to produce methanol and/or dimethyl ether.

Proponents:

Carbon Recycling International (CRI)

Mitsui Chemicals

ITEM	SPECIFIC SUB-CRITERION	SCORE	EVALUATION COMMENTS
Technology Maturity			
1.01	Timeframe to deployment	3	CRI is currently constructing a 5 million litre per annum commercial demonstration plant in Iceland. Publicly available information suggests the renewable methanol plant will be located adjacent to the 76.5MW Svartsengi Geothermal Power Station, which would in effect be the source of power and CO_2 (and potentially water) for the project. Methanol will be blended with conventional unleaded petrol and sold at Olis gasoline stations throughout the greater Reykjavik area. Mitsui Chemicals is operating a 100tpa pilot plant producing methanol from CO_2 and H_2. CO_2 is captured from ethylene production, whilst H_2 is produced from catalysed photolysis of water. The methanol is intended to be used in polymer synthesis, rather than as a liquid fuel.
Scale-Up Potential			
2.01	Scale-up potential	2	Displacement of 10 per cent of the world's fossil petroleum consumption with renewable methanol and/or dimethyl ether would represent in excess of 1Gtpa CO_2 recycling. Blends on the order of 10 per cent with conventional gasoline probably offers the most realistic route to large scale utilisation.

ITEM	SPECIFIC SUB-CRITERION	SCORE	EVALUATION COMMENTS
2.02	Geographical constraints on the production system	2	CRI's preferred plant embodiment/configuration co-locates with a geothermal power station and utilises the power station as the source of electricity and CO_2. Since the energy input to the system is electrical energy, production is possible anywhere in proximity to a CO_2 source and an electricity network. However, electricity grids with a lower CO_2 emissions intensity or a captive/dedicated renewable/zero emissions electricity supply for the project are realistically required to achieve any net decrease in CO_2 emissions as compared to fossil fuel alternatives. In the future, stand-alone methanol plants may be constructed including captive geothermal power generation.
Value for Money			
3.01	Commercial viability	2	Assume an unleaded petrol (gasoline) price equivalent of US$2/litre. On an energy equivalent basis, the methanol would be priced at US$1340/t methanol, or US$977/t CO_2 input. To break even without consideration for capital repayments, labour and other operating expenses, an electricity price of US$104/MWh would be required. This is readily achievable. Capital and operating cost estimates for the remainder of the plant are not available, so the overall commercial viability is more difficult to establish. Statements by CRI suggest the technology will be viable now in locations where the fuel price: electricity price ratio is large (e.g. Iceland). This is a reasonable statement.
3.02	Competitiveness with other emerging technologies	2	Electric vehicles are emerging as a viable alternative to liquid-fuelled vehicles. At present, they already have lower running costs than petroleum fuelled equivalent vehicles thanks to the relatively low cost of off-peak grid electricity and the benefits of regenerative braking. It is possible that in the longer-term electric vehicles will prove to be significantly cheaper.
3.03	Barriers / Incentives / Drivers	2	No major barriers identified

ITEM	SPECIFIC SUB-CRITERION	SCORE	EVALUATION COMMENTS
CO_2 Abatement Potential, Environmental and Social Benefits			
4.01	Permanence of Storage	1	For mobile transportation, it is reasonable to assume that capture of the CO_2 released from the combustion of methanol and/or dimethyl ether cannot practically be captured for further processing or reuse.
4.02	Additional CO_2 emissions from reuse	1	The CO_2 balance depends largely on the source of electricity. A dedicated renewable source of electricity has a very small emissions intensity, and consequently the additional emissions of CO_2 would be less than 0.5t CO_2 per tonne CO_2 reused. However, if grid power is used, the majority of countries have sufficiently high emissions intensity that the CO_2 balance is not so attractive. For example, Iceland, the location for the first proposed demonstration project, has an emissions intensity of 310kg CO_2 equiv/MWh. Assuming 65 per cent electrolysis and 75 per cent downstream methanol synthesis efficiency (realistic based on publicly available information), then the additional emissions would amount to 2.9MWh/t CO_2 reused. Because of this strong dependence on the electricity source, a moderate score is awarded. Edge Environment Case Study Result: 1.71t CO_2-e/t reused. Case Study Description: Capture from the Svartsengi Geothermal Power Plant (Iceland), process heat and power also supplied captively from this power station.
4.03	Environmental Benefit (Non CO_2 abatement related)	0	No additional specific environmental benefits have been identified.
4.04	Social Benefit (Non CO_2 abatement related)	0	No specific social benefits have been identified.
Developing Countries			
5.01	Applicability to developing countries	2	Favours any country with a low grid emissions intensity or large renewable energy potential (provided there are also concentrated CO_2 sources available). Does not specifically favour developing countries.

TECHNOLOGY: FORMIC ACID/HYDROGEN ECONOMY	DATE: 10/06/10

Technology Definition:

Electro-reduction of CO_2 to produce formic acid (HCOOH) and O_2. Formic acid is used as a hydrogen carrier, with hydrogen the primary fuel (classified as a liquid fuel as hydrogen is only released from the liquid formic acid as required).

Proponents:

ERC (Electroreduction of CO_2 to HCOOH and O_2) is being commercialised by Mantra Venture Group (Mantra).

No specific companies have been identified as proponents of formic acid to H_2 technology.

ITEM	SPECIFIC SUB-CRITERION	SCORE	EVALUATION COMMENTS
Technology Maturity			
1.01	Timeframe to deployment	1	Mantra claims to be close to commencing an ERC demonstration project (the CO_2 to formic acid part of the chain) of unspecified capacity in South Korea. However, there is no evidence of proponents developing the formic acid to H_2 part of the chain. It has been demonstrated (using for example a ruthenium catalyst and an aqueous solution of formic acid) by several research teams. It could be pursued commercially in the future should the CO_2 to formic acid part of the chain prove successful.

ITEM	SPECIFIC SUB-CRITERION	SCORE	EVALUATION COMMENTS
Scale-Up Potential			
2.01	Scale-up potential	3	The current formic acid market is 650,000tpa according to Mantra. The CO_2 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 CO_2, even if the entire current production system were to be replaced with ERC. In light of this, the present assessment of ERC for production of formic acid focuses on formic acid as a potential energy carrier and liquid fuel for transportation. Transport fuels are the logical focus because of their higher value than fuels for stationary power generation. Formic acid is typically not considered as a viable fuel for internal combustion engines, but rather for direct formic acid fuel cells, which are presently only proposed for small portable devices such as phones and laptops. However, as noted above formic acid has a relatively high hydrogen content per unit volume (better hydrogen density than gaseous elemental hydrogen at 350bar), and can therefore be viewed as a hydrogen carrier. The hydrogen can be released when an aqueous solution of formic acid is exposed to an appropriate catalyst. In this context, e.g. formic acid as an energy carrier in a hydrogen economy, the scale-up potential is significant. Displacement of 10 per cent of the world's fossil petroleum consumption with hydrogen carried by formic acid would represent in excess of 1Gtpa CO_2 recycling.
2.02	Geographical constraints on the production system	2	Since the energy input to the system is electrical energy, production is possible anywhere in proximity to a CO_2 source and an electricity network. However, electricity grids with a lower CO_2 emissions intensity or a captive / dedicated renewable / zero emissions electricity supply for the project are realistically required to achieve any net decrease in CO_2 emissions as compared to fossil fuel alternatives.

ITEM	SPECIFIC SUB-CRITERION	SCORE	EVALUATION COMMENTS
Value for Money			
3.01	Commercial viability	1	Mantra successfully completed a prototype capable of processing 1 kg of CO_2 per day in Oct. 2008, and its first commercial scale reactor, capable of producing 1 tonne of CO_2 a day, is scheduled for completion by Q2 2010. There is a lack of information about the potential economic feasibility of the technology on a commercial scale. Current predictions by Mantra state that the 'ERC technology could provide a net revenue of up to US$700 per tonne of CO_2' and that "the forecast return on investment for the user of ERC could be between 5 per cent and 20 per cent". However this only evidences the commercial viability of the first stage of the process (Formic Cid production) and not the subsequent conversion into a liquid fuel and assumes that the formic acid is sold into the current market where formic acid is selling at c.US$1,400/t. It can be estimated that on an energy equivalent basis, the formic acid produced for use as a liquid fuel would be priced at US$320/t formic acid, or US$338/t CO_2 input which would require an electricity price of US$42/MWh or less to break even on production price alone (which would be an optimistic assumption if the electricity were to be sourced from a renewable source). Furthermore, commercial viability of the technology will depend on the additional costs of CO_2 (e.g. capture and transport), capital costs for technology infrastructure and operating costs and expenses which will increase the breakeven price of electricity further. If the first stage were proved to be viable then in order for the use of formic acid as a liquid fuel for transportation to become large scale then it would need to economically feasible on a large scale such that the production and sale of the fuel was competitive against existing alternatives such as petroleum. Given that petroleum prices are currently in the region of US$2/litre it is unlikely that formic acid as a liquid fuel would be able to compete in this market. Hence, unless significant reductions in cost can be made, large scale commercialisation is unlikely given the prevailing price of petroleum. The lack of information currently available and limited demonstration projects means that the commercial and economic viability of the technology is very much uncertain at this stage.

ITEM	SPECIFIC SUB-CRITERION	SCORE	EVALUATION COMMENTS
3.02	Competitiveness with other emerging technologies	1	With a current formic acid market of 650,000tpa there is a strong existing market for the by-product of the ERC technology for use in existing applications, with Western Europe being the largest consumer. However this offers relatively few significant growth prospects. 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/L displacing these alternatives given the current estimates appears to be unlikely. If formic acid as a liquid fuel can be shown to be commercially viable then demand for formic acid is likely to increase more significantly than current forecasts. This could result in current supply outstripping demand and provide an opportunity for entry into the market. However, it is difficult to estimate the likelihood of this.
3.03	Barriers / Incentives / Drivers	2	The National Research Council of Canada Industrial Research Assistance Program (NRC-IRAP) has agreed to fund 50 per cent of the costs associated with the development of Mantra's ERC technology. ERC by-products represent useful and financially profitable sources of income however there is still uncertainty over whether these will be price competitive. Formic acid market is largely dominated by Western Europe which may limit opportunities in other regions.
CO_2 Abatement Potential, Environmental and Social Benefits			
4.01	Permanence of Storage	1	The main application considered in the present assessment is formic acid as a hydrogen carrier for transport fuels (see discussion in 2.01). As a transport fuel, it is reasonable to assume that capture of the CO_2 released from the formic acid when hydrogen is produced cannot practically be captured for further processing or reuse.

ITEM	SPECIFIC SUB-CRITERION	SCORE	EVALUATION COMMENTS
4.02	Additional CO_2 emissions from reuse	1	Publicly available information on the ERC process indicates 8MWh/t CO_2 energy input requirement. The CO_2 balance depends largely on the source of electricity. A dedicated renewable source of electricity has a very small emissions intensity, and consequently the emissions of CO_2 would be less than 0.5t CO_2 per tonne CO_2 reused. However, if grid power is used, the majority of countries have sufficiently high emissions intensity that the CO_2 balance is not so attractive. South Korea (proposed demonstration project location) has an emissions intensity of approximately 440kg CO_2 equivalent / MWh. Consequently, a grid powered ERC project in South Korea would emit 3.5t+ CO_2 per tonne of CO_2 reused. In other words, direct emissions of fossil fuel from a power station combined with direct use of fossil fuels as a transport fuel would have a lower emissions intensity. Because of this strong dependence on the electricity source and the fact that it is not publicly stated that the input to the demonstration project will be purely from renewable electricity sources, a moderate score is awarded. Details on the current performance of catalysed decomposition of formic acid have not been further investigated. Edge Environment Case Study Result: 3.96t CO_2-e/t reused. Case Study Description: Capture from a coal-fired power station in Korea, supplying CO_2 to the electrolysis plant via a 9km pipeline.
4.03	Environmental Benefit (Non CO_2 abatement related)	0	No additional specific environmental benefits have been identified.
4.04	Social Benefit (Non CO_2 abatement related)	0	No specific social benefits have been identified.
Developing Countries			
5.01	Applicability to developing countries	2	Favours any country with a low grid emissions intensity or large renewable energy potential (provided there are also concentrated CO_2 sources available). Does not specifically favour developing countries.

TECHNOLOGY: ENHANCED COAL BED METHANE RECOVERY (ECBM)	DATE: 18/06/10

Technology Definition:

ECBM involves flooding coal seams with injected CO_2, where it's adsorbed by coal, in turn displacing methane to the surface for it to be captured and consumed as fuel.

Proponents:

Proponents of CO_2 ECBM concentrate around Western governments with large coal reserves, such as the US, Europe, Canada, Australia and New Zealand with funding to support development of the technology. ECBM could progress to developing countries which possess large coal reserves, although this is only expected to happen once research is more advanced and projects underway in the developed world have proved successful. The Chinese government are interested in this technology due to a high dependence on coal power plants.

Companies such as Solid Energy UCG (underground coal gasification), Alkane Energy, Edeco, Thompson FW, and larger mining entities would play a role in the ECBM market. Others include commercial gas companies such as Air Liquid, oil companies like BP, ConocoPhillips, Dow Chemical and emerging companies such as Sproule Industry, Suncor Energy Inc. and Tesseract Corporation. Research institutions such as ETH Zurich, the Japan Coal Energy Centre, Alberta University and the Netherlands Institute of Applied Geoscience are also researching the technology.

ITEM	SPECIFIC SUB-CRITERION	SCORE	EVALUATION COMMENTS
Technology Maturity			
1.01	Timeframe to deployment	2	CO_2 ECBM technology is still in a development phase. Pilot plants have been operating since 1997, however as its application is very location specific. Country and region research continues in the Western world through government funding while developing countries are not investing in CO_2 ECBM, apart from China due to the country's high dependence on coal power plants Therefore, the timeframe to commercial deployment is considered a minimum of five years away, potentially accelerated through demand for natural gas supply.

ITEM	SPECIFIC SUB-CRITERION	SCORE	EVALUATION COMMENTS
Scale-Up Potential			
2.01	Scale-up potential	3	Coal seams are the most abundant fossil fuel deposits (in comparison to oil and gas reservoirs) so there is potential for ECBM to become widespread on unmineable coal seams if commercial deployment is achieved. Results from research held in 29 possible ECBM sites in China have determined that CO_2 sequestration potential is about 143 Gt in the country's known coal beds. This could sequester CO_2 emissions for an estimated 50 years based on China's CO_2 emission levels in 2000.
2.02	Geographical constraints on the production system	2	CO_2 ECBM is specific to location, applicable to countries with large coal reserves, which are not being mined. CO_2 source, transport options and associated cost compared to the revenue of gas production will determine if ECBM is cost effective for investment. While scale-up potential exists, coal beds need to be assessed on a case by case basis to determine if a cost effective method for ECBM. Other factors will affect ECBM application, such as competition from companies wanting to mine coal. If un-mineable (e.g. due to being offshore, in a residential area or deep underground), the cost of ECBM recovery will increase.

ITEM	SPECIFIC SUB-CRITERION	SCORE	EVALUATION COMMENTS
Value for Money			
3.01	Commercial viability	2	CO_2/nitrogen injection into coal seams can be economic if the value of the produced gas exceeds the cost of producing the gas, plus the cost of transporting the gas minus the cost of taxes or CO_2 credits. Theoretically, coal bed methane fairway shows exceptional promise for commercial application because (1) the coal bed methane industry represents a substantial market for CO_2 and (2) if there are local coal-fired power plants, they could potentially produce CO_2 in enough quantity to facilitate enhanced coal bed methane recovery at a large scale. Generally however, ECBM technology would have to improve to ensure economical recovery. In a recent study performed by the Alberta Research Council testing CO_2 and ECBM in Alberta's coal beds, it was concluded that since it took at least two cubic feet of CO_2 for each cubic foot of methane produced, the CO_2 cost would take up more than $2 of the gas price on a per thousand cubic feet of methane basis (assuming CO_2 at $1 per thousand standard cubic feet or $19 per tonne.) Flue gas (CO_2 and N_2) potentially offers a more commercially viable solution. Despite this and a few other studies that have taken place, the factors still limiting the implementation of ECBM recovery are economical, e.g. lack of penalties for CO_2 emissions, as well as technological and scientific, e.g. limited understanding of fundamental issues related to ECBM. For example, if CO_2 credits increase in value, it could make a commercially unviable project viable. Actual project economics will depend on site-specific considerations, operational characteristics, and numerous other factors, and the economics for a specific situation could differ considerably from others. The main considerations would be: • cost of CO_2; • availability of injectant gas; • value of methane; • cost of processing; • cost of implementation; and • transportation.

ITEM	SPECIFIC SUB-CRITERION	SCORE	EVALUATION COMMENTS
3.02	Competitiveness with other emerging technologies	3	The ECBM process appears always to rely on the use of CO_2, although this may be mixed with nitrogen. The Alberta study has shown that flue gas (which comprises mainly of nitrogen and carbon dioxide) injection has its merits. From an economic perspective, flue gas injection offered better economics than pure CO_2 injection (unless there is a credit for CO_2). Flue gas injection appears to enhance methane production to a greater degree possible than with CO_2 alone while still sequestering CO_2, albeit in smaller quantities Therefore, considering both economic and CO_2 sequestration factors, there might be an ideal CO_2/N_2 composition where both factors will be optimised. ECBM's predecessor, 'Coal Bed Methane', involved burning or gasifying the subterranean coal and collecting the resulting methane, but this was difficult and hard to control. Therefore ECBM is an improvement on previous methods.
3.03	Barriers / Incentives / Drivers	2	The potential barriers or limitations to ECBM fall into the three broad categories: geologic, economic, and policy. The geologic limitations are fixed in the absence of advances in technology; if the gas is not present in commercial quantities or if the gas cannot be produced, the project would not support an ECBM project, especially given the additional costs. Assuming favourable geologic characteristics, the operator must then examine the economics of the project. A wide variety of factors can influence project economics, and thus, the likely application of ECBM processes in mineable coal seams. Finally, regulatory requirements and/or potential financial incentives can tip the balance for or against marginal projects. ECBM recovery operations will make use of existing facilities by converting production wells for injection and will use time-tested technological approaches, such as organisation of injection wells and production wells in five-spot patterns, so there is scope for ECBM to take advantage of existing infrastructure.
CO_2 Abatement Potential, Environmental and Social Benefits			
4.01	Permanence of Storage	3	ECBM floods coal beds where the CO_2 is adsorbed by the coal, in turn displacing methane to the surface for it to be captured and consumed as fuel. Unlike EOR where CO_2 forms a miscible solution with the oil and returns to the surface, injected CO_2 remains with the coal bed. Therefore CO_2 sequestered will have permanent storage if the coal is not mined and combusted post ECBM.

ITEM	SPECIFIC SUB-CRITERION	SCORE	EVALUATION COMMENTS
4.02	Lifecycle CO_2 analysis	3	While having permanent storage for the injection stream, a secondary CO_2 source is created in the ECBM process assuming the natural gas produced is combusted as heating fuel. Natural gas is cleanest fossil fuel in that it produces the least amount of CO_2 when burnt so this could be considered a benefit over the emissions created from mining and combusting the coal deposit directly. A study carried out in Alberta, Canada, where pure CO_2 was injected into an 80-acre plot via a 5-spot pattern indicated that low-rank coal can store 1.27–2.25 BCF of CO_2, whilst ECMB recovery reached levels of 0.62 – 1.10 BCF of natural gas. Therefore, the injection recovery rate for CO_2 to CH_4 is 2:1 across the range stated above. As an example, when 2000CF of CO_2 (112kg CO_2) is injected, 1000CF of NG (assuming pure) will be produced. If this gas is then combusted in entirety at STP (0°C, 1atm), approximately 56kg of CO_2 is produced. Another CO_2 contribution needs to be considered in the ECBM life cycle, assuming grid power dependence to capture, compress and inject CO_2 from a point source, for every tonne of CO_2 injected into a well, 310 kg CO_2 is released from power generation with a carbon density of 0.89 tCO_2/ MWh, to supply the CCS chain with 350 KWh/tCO_2 injected. Combined feedstock generation and natural gas combustion emissions tCO_2 per tCO_2 reused will be > 0.5t/t. Edge Environment Case Study Result: 0.44t CO_2-e/t reused Case Study Description: Capture from a coal-fired power station in China (Yancheng), supplying a commercial ECBM operation in the South Quinshui Basin via a 50km pipeline
4.03	Environmental Benefit (Non CO_2 abatement related)	0	No additional specific environmental benefits have been identified.
4.04	Social Benefit (Non CO_2 abatement related)	0	No specific social benefits have been identified.

ITEM	SPECIFIC SUB-CRITERION	SCORE	EVALUATION COMMENTS
Developing Countries			
5.01	Applicability to developing countries	3	With significant interest from developing countries such as China and Indonesia, who have an increasing demand for reliable energy supply in growing economies, ECBM being economically viable without a carbon price, is considered to have greater potential of deployment in developing countries than developed countries.

APPENDIX L: EMERGING TECHNOLOGIES – DEMONSTRATION PROJECTS AND R&D STUDIES

Table L.1 Demonstration

PROJECT NAME/ COMPANY	TECHNOLOGY	DESCRIPTION	FUNDING	LOCATION	REFERENCE
Touchstone Research Laboratory Ltd	Algae cultivation	This project will pilot-test an open-pond algae production technology that can capture at least 60 per cent of flue gas CO_2 from an industrial coal-fired source to produce biofuel and other high value co-products. A novel phase change material incorporated in Touchstone's technology will cover the algae pond surface to regulate daily temperature, reduce evaporation, and control the infiltration of invasive species. Lipids extracted from harvested algae will be converted to a bio-fuel, and an anaerobic digestion process will be developed and tested for converting residual biomass into methane. The host site for the pilot project is Cedar Lane Farms in Wooster, Ohio.	DOE Share: US$6.24M	Triadelphia, W. Va	
Solazyme	Algae cultivation	The company uses algal biotechnology to renewably produce clean fuels, chemicals, foods and health science products. Solazyme's advanced and proprietary technology uses algae to produce oils and biomaterials in standard fermentation facilities quickly, cleanly, cost effectively, and at large scale.			

PROJECT NAME/ COMPANY	TECHNOLOGY	DESCRIPTION	FUNDING	LOCATION	REFERENCE
MBD	Algae cultivation	MBD technology recycles captured industrial flue-gas emissions into oils suitable for manufacture of high grade plastics, transport fuel and nutritious feed for livestock and monogastric consumption. MBD Energy has reached agreements with three of Australia's largest greenhouse gas emitters: • Loy Yang A (Vic); • Eraring Energy (NSW); and • Tarong Energy (Qld). The agreements are for the planning and provision of a pilot MBD Energy Carbon Capture and Recycling (CCR) plant at each location.		Aus	http://www.mbdenergy.com/
A2BE Carbon Capture	Algae cultivation	A2BE Carbon Capture is developing bio-secure, scalable, climate adaptive, and highly cost effective technology for producing valuable fuel and food from CO_2 using algal photosynthesis and bio-harvesting. The core of this technology is embodied in the published US patent application 20070048848: 'Method, apparatus and system for biodiesel production from algae' as well as a separate mechanical and a PCT patent application.		CO, USA	http://www.algaeatwork.com/technology/
Honeywell UOP	Algae cultivation	The project, managed by the DOE's National Energy Technology Laboratory, will capture CO_2 from the exhaust stacks of the Hopewell caprolactam facility and deliver it in a controlled and efficient process to a pond near the plant, where algae will be grown using automated control systems from Honeywell Process Solutions and technology developed by New Zealand's Aquaflow Bionomic.	DOE: US$1.5M	VA, USA	http://www.uop.com/pr/releases/DOE%20Hopewell%20Grant%20PR%20-%20FINAL.pdf

PROJECT NAME/ COMPANY	TECHNOLOGY	DESCRIPTION	FUNDING	LOCATION	REFERENCE
Carbon Capture Corporation	Algae cultivation	Carbon Capture Corporation's pilot facility uses two Capstone C330 (30 kW each) running on propane and used to generate emissions – resembling those from a natural gas fired power facility – that are fed into one of the two dedicated 240,000-gallon raceways where Spirulina algae is produced and harvested. In addition to actual production data and costs, the pilot test is expected to provide valuable insight regarding air and water chemistry associated with the process. The Company operates open algae ponds with a total capacity of 8 million gallons located on an existing 40-acre Algae Research Center (ARC) which is part of a 326-acre research and development facility in Imperial Valley, California.		CA, USA	http://www.carbcc.com/21323/index.html
Algenol and the Linde Group	Algae cultivation	Algenol and Linde have agreed to collaborate in a joint development project to identify the optimum management of carbon dioxide and oxygen for Algenol's unique algae and photobioreactor technology. This cooperation will see the companies join forces to develop cost-efficient technologies that capture, store, transport and supply carbon dioxide for Algenol's proprietary process as well as remove oxygen from the photobioreactor.			http://www.algenolbiofuels.com/linde.htm
Algenol and The Dow Chemical Company	Algae cultivation	Dow and Algenol are exploring ways to reduce the cost and improve the efficiency of capturing carbon dioxide for use in producing ethanol or other high value organic chemicals.			http://www.algenolbiofuels.com/dow.htm
Algenol and Biofields	Algae cultivation	BioFields is a Mexican business group dedicated to the production of ethanol from hybrid blue-green algae, sunlight, CO_2 capture, non-agricultural land and salt water to help in the fight against climate change and offer an alternative to meet future energy demand with the highest levels of sustainability.		Mexico	http://www.algenolbiofuels.com/biofields.htm

PROJECT NAME/ COMPANY	TECHNOLOGY	DESCRIPTION	FUNDING	LOCATION	REFERENCE
RWE	Algae cultivation	Near the Niederaussem power plant, RWE power has erected a system for binding CO_2 from the power plant into micro-algae. In this process the flue gas is drawn from the power plant unit and transported through the pipes to the micro-algae production plant. The CO_2 contained in the flue gas is dissolved in the algae suspension and absorbed by the algae for growth. The algae are removed and further investigated for conversion into chemically or energetically usable products.		Germany	http://www.rwe.com/web/cms/mediablob/en/247480/data/235578/32311/rwe-power-ag/media- center/lignite/blob.pdf
Alcoa, Inc	Bauxite residue carbonation	Alcoa's pilot-scale process will demonstrate the high efficiency conversion of flue gas CO_2 into soluble bicarbonate and carbonate using an in-duct scrubber system featuring an enzyme catalyst. The bicarbonate/carbonate scrubber blow down can be sequestered as solid mineral carbonates after reacting with alkaline clay, a by-product of aluminium refining. The carbonate product can be utilised as construction fill material, soil amendments, and green fertiliser. Alcoa will demonstrate and optimise the process at their Point Comfort, Texas aluminium refining plant.	DOE Share: US$12M	Alcoa Center, Pa	
Calera Corporation	Carbonate mineralisation	Calera Corporation is developing a process that directly mineralises CO_2 in flue gas to carbonates that can be converted into useful construction materials. An existing CO_2 absorption facility for the project is operational at Moss Landing, California, for capture and mineralisation. The project team will complete the detailed design, construction, and operation of a building material production system that at smaller scales has produced carbonate-containing aggregates suitable as construction fill or partial feedstock for use at cement production facilities. The building material production system will ultimately be integrated with the absorption facility to demonstrate viable process operation at a significant scale.	DOE Share: US$19.9M	Los Gatos, Ca, US	

PROJECT NAME/ COMPANY	TECHNOLOGY	DESCRIPTION	FUNDING	LOCATION	REFERENCE
Skyonic Corporation	Carbonate mineralisation	Skyonic Corporation will continue the development of SkyMine® mineralisation technology – a potential replacement for existing scrubber technology. The SkyMine process transforms CO_2 into solid carbonate and/or bicarbonate materials while also removing sulfur oxides, nitrogen dioxide, mercury and other heavy metals from flue gas streams of industrial processes. Solid carbonates are ideal for long-term, safe above ground storage without pipelines, subterranean injection, or concern about CO_2 re-release to the atmosphere. The project team plans to process CO_2-laden flue gas from a Capital Aggregates, Ltd. cement manufacturing plant in San Antonio, Texas.	DOE Share: US$25M	Austin, Texas	
Carbon Sense Solutions	Concrete curing	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. With financial competitiveness in mind, Carbon Sense Solutions' approach limits the need to steam-cure products, which reduces energy costs for manufacturers and increases productivity. This transformative process operates by consuming substantial amounts of CO_2 from onsite and neighbouring combustion sources.		Nova Scotia, Canada	http://carbonsensesolutions.com/technology/

PROJECT NAME/ COMPANY	TECHNOLOGY	DESCRIPTION	FUNDING	LOCATION	REFERENCE
Burlington Resources US Department of Energy (DOE) National Energy Technology Laboratory Advanced Resources Intl	Enhanced coal bed methane	Burlington Resources operated the Allison Unit as the first 'commercial-scale' field project of ECBM technology using CO_2. This site consists of 16 producer wells and 4 injectors. CO_2 injection operations commenced in 1995, providing a substantial history for understanding the in-situ reservoir mechanics associated with CO_2 injection. Development and demonstration of application of ECBM reservoir modelling techniques continued with field studies from 2000-1008 to understand the reservoir mechanisms of CO_2 injection into coal seams, demonstrate the practical effectiveness of the ECBM and sequestration processes and an engineering capability to simulate them, evaluate sequestration economics, and document field procedures.	US DOE Share: US$1.4M Private share: US$5.76M	San Juan County, Southern New Mexico	http://www.co2captureandstorage.info/project_specific.php?project_id=37
GreenFire Energy/ Enhanced Energy Resources	Enhanced geothermal systems	Joint venture of GreenFire Energy with Enhanced Oil Resources joint plan to build a 2MW CO_2 based demonstration plant near the Arizona-new Mexico border. Drilling of wells to access hot rock was proposed to commence in 2010. The proposed location is projected to yield enough heat to generate 800 MW of power with potential to absorb much of the CO_2 generated by six large coal-fired plants in the region.			

PROJECT NAME/ COMPANY	TECHNOLOGY	DESCRIPTION	FUNDING	LOCATION	REFERENCE
Geodynamics Limited	Enhanced geothermal systems	Geodynamics Limited Innamincka 'Deeps' Joint Venture with Origin Energy. A 1 MW power plant has been constructed at Habanero. Electricity generation is expected to occur by early 2012 following the successful completion of Habanero 4 and Habanero 5 (reservoirs) – which will be the first Enhanced Geothermal Systems in Australia. Due to make final investment decision on proposed $300 million, 25MW geothermal demonstration plant in the Cooper Basin by early 2013, after 12 months of successful operation of the Habanero closed loop. (This is two years later than previously stated). Geodynamics is targeting production of more than 500 MW by 2018, with capacity extending to 10,000 MW – the equivalent of 10 to 15 coal-fired power stations. Geodynamics Ltd, is one of about 16 companies active in geothermal power generation in Australia (and are the most advanced).			
Symyx Technologies	Enhanced geothermal systems	Symyx Technologies are studying the chemical interactions between geothermal rocks, supercritical carbon dioxide and water. Testing the use of supercritical CO_2 as the working fluid in geothermal systems is projected to commence in 2013.			

PROJECT NAME/ COMPANY	TECHNOLOGY	DESCRIPTION	FUNDING	LOCATION	REFERENCE
Phycal, LLC	Liquid fuel	Phycal will complete development of an integrated system designed to produce liquid biocrude fuel from microalgae cultivated with captured CO_2. The algal biocrude can be blended with other fuels for power generation or processed into a variety of renewable drop-in replacement fuels such as jet fuel and biodiesel. Phycal will design, build, and operate a CO_2-to-algae-to-biofuels facility at a nominal thirty acre site in Central O'ahu (near Wahiawa and Kapolei), Hawaii. Hawaii Electric Company will qualify the biocrude for boiler use, and Tesoro will supply CO_2 and evaluate fuel products.	DOE Share: US$24.24M	Highland Heights, Ohio, US	
Carbon Recycling International	Liquid fuel	Icelandic company Carbon Recycling International (CRI) is in the process of building a plant that will capture carbon dioxide from industrial emissions and converts carbon dioxide into clean Renewable Methanol (RM) fuel. RM can be blended with different grades of gasoline for existing automobiles and hybrid flexible vehicles.		Iceland	http://www. carbon recycling.is/
Carbon Sciences	Liquid fuel	Carbon Sciences is developing a breakthrough CO_2 based gas-to-liquids technology to transform greenhouse gases into liquid portable fuels, such as gasoline, diesel and jet fuel.		CA, USA	http://www. carbons ciences.com/
Mantra Venture Group	Liquid fuel	In using renewable energy, Mantra's Electroreduction of Carbon Dioxide (ERC) technology combines captured CO_2 with water to produce high value materials, including: formic acid, formate salts, oxalic acid, and methanol. In addition, companies adopting ERC stand to make significant profit from its by-products. Mantra has successfully completed the year-long development program for its ERC technology and the company is now preparing for its first-ever on-site demonstration project.	National Research Council of Canada Industrial Research Assistance Program (NRC-IRAP): unknown amount	WA, USA	http://www. mantra energy. com/news/

PROJECT NAME/ COMPANY	TECHNOLOGY	DESCRIPTION	FUNDING	LOCATION	REFERENCE
Joule Unlimited	Liquid fuel	Joule's Helioculture™ platform combines breakthroughs in genome engineering, bioprocessing and hardware engineering to convert sunlight and waste CO_2 directly into clean, fungible diesel fuel, bypassing the limitations of biofuel production. The novel SolarConverter™ system is optimised to facilitate the entire continuous process, scaling to desired output levels with no dependency on raw material feedstocks, agricultural land, fresh water or crops. The Texas-based pilot facility is expected to be up and running mid 2010, centred on producing clean, fungible diesel. A demonstration facility is expected to follow the pilot plant in the summer of 2011, with a commercial facility in 2012 centred on diesel. Sims said Joule expects to be fully commercial by 2013.	Flagship Ventures: US$30M	MA, USA	http://www.jouleunlimited.com/about/overview

PROJECT NAME/ COMPANY	TECHNOLOGY	DESCRIPTION	FUNDING	LOCATION	REFERENCE
Sandia National Lab	Liquid fuel	Using concentrated solar energy to reverses combustion, Sandia National Laboratories chemically 'reenergises' carbon dioxide into carbon monoxide using concentrated solar power. The carbon monoxide could then be used to make hydrogen or serve as a building block to synthesise a liquid combustible fuel, such as methanol or even gasoline, diesel and jet fuel. An alliance of industry, academic and government organisations, formed to commercialise technologies that will utilise concentrated solar energy to convert waste carbon dioxide into diesel fuel. The alliance team members include Sandia National Laboratories, Renewable Energy Institute International (REII), Pacific Renewable Fuels, Pratt Whitney Rocketdyne (a United Technologies Division), Quanta Services, Desert Research Institute and Clean Energy Systems. In addition, commercial partners have signed on to advance work on the first round of commercial plants. A solar reforming system is currently being demonstrated in Sacramento, California, and demonstrations will continue both at Sandia's facilities in New Mexico and at a power plant project site in Bakersfield, California. Planning for the first round of commercial plants is under way at several locations in the US The project team anticipates that deployment of the first commercial plants can begin in 2013.	National Energy Technology Laboratory : Unknown amount	Various, USA	https://share.sandia.gov/news/resources/news_releases/alliance-formed-to-commercialize-technologies-that-convert-waste-co$_2$-into-diesel-fuel-using-solar-energy/

PROJECT NAME/ COMPANY	TECHNOLOGY	DESCRIPTION	FUNDING	LOCATION	REFERENCE
Novomer Inc.	Polymer processing	Teaming with Albemarle Corporation and the Eastman Kodak Company, Novomer will develop a process for converting waste CO_2 into a number of polycarbonate products (plastics) for use in the packaging industry. Novomer's novel catalyst technology enables CO_2 to react with petrochemical epoxides to create a family of thermoplastic polymers that are up to 50 per cent by weight CO_2. The project has the potential to convert CO_2 from an industrial waste stream into a lasting material that can be used in the manufacture of bottles, films, laminates, coatings on food and beverage cans, and in other wood and metal surface applications. Novomer has secured site commitments in Rochester, NY, Baton Rouge, Louisiana, Orangeburg, SC and Ithaca, NY where Phase 2 work will be performed.	DOE Share: US$18.42M	Ithaca, NY	

Table L.2 Research

PROJECT NAME/ COMPANY	TECHNOLOGY	DESCRIPTION	FUNDING	LOCATION	REFERENCE
Brown University	Acrylate compound synthesis	Researchers will demonstrate the viability of a bench-scale reaction using CO_2 and ethylene as reactants to produce valuable acrylate compounds with low-valent molybdenum catalysts. Exploratory experiments will be conducted to identify the factors that control the current catalyst-limiting step in acrylic acid formation.	DOE share: US$417,155	Providence, R.I.) –	http://www.netl.doe.gov/publications/press/2010/100706-Research_Projects_To_Convert.html
CCS Materials, Inc	Carbonate mineralisation	Investigators will attempt to create an energy efficient, CO_2-consuming inorganic binding phase to serve as a high-performing substitute for Portland cement (PC) in concrete. The project team will use a novel near-net-shape forming process that uses a binding phase based on carbonation chemistry instead of the hydration chemistry used in PC concrete.	DOE share: US$794,000	Piscataway, NJ	http://www.netl.doe.gov/publications/press/2010/100706-Research_Projects_To_Convert.html
Research Triangle Institute	Chemical synthesis	RTI will assess the feasibility of producing valuable chemicals, such as carbon monoxide, by reducing CO_2 using abundant low-value carbon sources, such as petcoke, sub-bituminous coal, lignite, and biomass, as the reductant. The team will then evaluate whether additional processes can be added that use the carbon monoxide to produce other marketable chemicals, such as aldehydes, ketones, carboxylic acids, anhydrides, esters, amides, imides, carbonates, and ureas.	DOE share: US$800,000	Durham, NC	http://www.netl.doe.gov/publications/press/2010/100706-Research_Projects_To_Convert.html

PROJECT NAME/ COMPANY	TECHNOLOGY	DESCRIPTION	FUNDING	LOCATION	REFERENCE
PhosphorTech Corpora	Chemical synthesis	Investigators will develop and demonstrate an electrochemical process using a light-harvesting CO_2 catalyst to reform CO_2 into products such as methane gas. Researchers hope to achieve a commercially feasible CO_2 reforming process that will produce useful commodities using the entire solar spectrum.	DOE share: US$998,661	Lithia Springs, Ga	http://www.netl.doe.gov/publications/press/2010/100706-Research_Projects_To_Convert.html
McGill University	Concrete curing	In collaboration with 3H Company (Lexington, Ky.), researchers aim to develop a curing process for the precast concrete industry that uses CO_2 as a reactant. To make the process economically feasible, a self-concentrating absorption technology will be studied to produce low-cost CO_2 for concrete curing and to capture residual carbon after the process.	DOE share: US$399,960	Quebec, Canada	http://www.netl.doe.gov/publications/press/2010/100706-Research_Projects_To_Convert.html
CO_2 as Fluid – Berkeley Lab	Enhanced geothermal systems	Instead of water as the heat transmission fluid, this project will examine the feasibility of using carbon dioxide. Theoretical studies have indicated that CO_2 may extract heat from fracture rock at about 50 per cent higher rates than water. This project is a collaboration with Idaho National Laboratory.		California, USA	http://newscenter.lbl.gov/news-releases/2009/ 10/29/berkeley-lab-receives-7-million-for-enhanced-geothermal-energy-technologies/

PROJECT NAME/ COMPANY	TECHNOLOGY	DESCRIPTION	FUNDING	LOCATION	REFERENCE
Massachusetts Institute of Technology	Liquid fuel	In this project, researchers will investigate a novel electrochemical technology that uses CO_2 from dilute gas streams generated at industrial carbon emitters, including power plants, as a raw material to produce useful commodity chemicals. This integrated capture and conversion process will be used to produce a number of different chemicals that could replace petroleum-derived products.	DOE share: US$1M	MA, USA	http://www.netl.doe.gov/publications/press/2010/100706-Research_Projects_To_Convert.html
Institute of Bioengineering and Nanotechnology (IBN)	Liquid fuel	Scientists at the Singapore-based Institute of Bioengineering and Nanotechnology (IBN) have made an unprecedented breakthrough in transforming carbon dioxide, a common greenhouse gas, into methanol, a widely used form of industrial feedstock and clean-burning biofuel. Using 'organocatalysts', researchers activated carbon dioxide in a mild and non-toxic process to produce the more useful chemical compound.		Singapore	http://www.gizmag.com/research-carbon-dioxide-methanol/11483/
University of California	Liquid fuel	Their method for producing methanol from a geothermal energy source includes (1) obtaining carbon dioxide and water or steam from the geothermal source; (2) generating hydrogen from the steam, isolating the carbon dioxide accompanying the water or steam source; and (3) converting the isolated carbon dioxide and generated hydrogen to methanol. The isolated carbon dioxide and generated hydrogen are obtained solely from the geothermal source and the geothermal source provides energy necessary for the production of methanol.		California, USA	http://www.zimbio.com/Global+Warming/articles/qs- z1B2HGZL/Nano technology +Carbon+Capture+Endless +Fuel

PROJECT NAME/ COMPANY	TECHNOLOGY	DESCRIPTION	FUNDING	LOCATION	REFERENCE
Pennsylvania State University	Liquid fuel	Using natural outdoor sunlight, Penn State have achieved efficient solar conversion of CO_2 and water vapor to methane and other more complex hydrocarbons using high surface area nitrogen doped nanotube arrays, sensitised with nanodimensional islands of co-catalysts copper and Ni, Pd or Pt. The 'Towards Scale Solar Conversion of CO_2 and Water Vapor to Hydrocarbon' project seeks to build upon their preliminary efforts to achieve ≈2 per cent sunlight to chemical fuel conversion efficiency via CO_2 reduction. Phase II will implement a standalone 9m^2 pilot plant collector for high rate solar photocatalytic reduction of CO_2 and water vapor producing fuel equivalent to approx. ≈ 165L of natural gas.	Advanced Research Projects Agency-Energy: US$1.9M	PA, USA	http://arpa-e.energy.gov/LinkClick.aspx?fileticket=mh9dFaaUuv8%3d&tabid=209
Ohio State University	Liquid fuel	Bioconversion of CO_2 to biofuels is a technology for the efficient bioconversion of CO_2 into an infrastructure-compatible liquid biofuel, butanol, without using photosynthesis. The project includes genetic modifications of bacteria that metabolise CO_2, oxygen and hydrogen to produce butanol; development of an industrially scalable bioreactor system; and a novel approach to recovery of butanol from the bioreactor.	Advanced Research Projects Agency: US$4M	OH, USA	http://arpa-e.energy.gov/LinkClick.aspx?fileticket=AxnsMo3ONYs%3d&tabid=83
Massachusetts Institute of Technology – Production of Isobutanol Motor Fuel from CO_2, Hydrogen and Oxygen	Liquid fuel	This project relies on microbes that use hydrogen to convert carbon dioxide into liquid transportation fuels. The project will develop a system using Ralstonia eutropha to redirect carbon flux to butanol production in a novel bioreactor system with increased performance.	Advanced Research Projects Agency: US$1.77M	MA, USA	http://arpa-e.energy.gov/LinkClick.aspx?fileticket=AxnsMo3ONYs%3d&tabid=83

PROJECT NAME/ COMPANY	TECHNOLOGY	DESCRIPTION	FUNDING	LOCATION	REFERENCE
Massachusetts Institute of Technology – Bioprocess and Microbe Engineering for Total Carbon Utilisation in Biofuel Production	Liquid fuel	This project will develop a process to combine an anaerobic carbon dioxide-fixing microbe in one stage with an aerobic oil-producing microbe in a second stage. The net effect would be the production of oil for biodiesel from carbon dioxide and hydrogen or electricity.	Advanced Research Projects Agency: US$3.2M	MA, USA	http://arpa-e.energy.gov/LinkClick.aspx?fileticket=AxnsMo3ONYs%3d&tabid=83
OPX Biotechnologies	Liquid fuel	This project will develop and optimise a novel, engineered microorganism that produces a biodiesel-equivalent fuel from renewable hydrogen and carbon dioxide. Water will be the primary by-product.	Advanced Research Projects Agency: US$6M	CO, USA	http://arpa-e.energy.gov/LinkClick.aspx?fileticket=AxnsMo3ONYs%3d&tabid=84
Medical University of South Carolina – Bioelectrochemical Reduction of CO_2 to Butanol	Liquid fuel	This project will develop a microbially catalysed electrolysis cell that uses electricity (e.g. from solar PV) to convert carbon dioxide into liquid alcohol fuels. The process will produce butanol and will also be able to produce ethanol.	Advanced Research Projects Agency: US$2.3M	SC, USA	http://arpa-e.energy.gov/LinkClick.aspx?fileticket=AxnsMo3ONYs%3d&tabid=85
Columbia University – Biofuels from CO_2 using Ammonia-Oxidising bacteria in a reverse microbial fuel cell	Liquid fuel	This project will use an ammonia-oxidising bacteria to produce isobutanol from carbon dioxide.	Advanced Research Projects Agency: US$0.5M	NY, USA	http://arpa-e.energy.gov/LinkClick.aspx?fileticket=AxnsMo3ONYs%3d&tabid=86

PROJECT NAME/ COMPANY	TECHNOLOGY	DESCRIPTION	FUNDING	LOCATION	REFERENCE
Lawrence Berkeley National Laboratory – Development of an Integrated Microbial-ElectroCatalytic System for Liquid Biofuel production from CO_2	Liquid fuel	This project will develop a novel, combined microbial and electrochemical catalytic system to convert hydrogen and carbon dioxide into energy-dense biofuels.	Advanced Research Projects Agency: US$3.9M	CA, USA	http://arpa-e.energy.gov/LinkClick.aspx?fileticket=AxnsMo3ONYs%3d&tabid=87
Solar2Fuel – BASF, Energie Baden-Württemberg AG (EnBW), Heidelberg University and Karlsruhe Institute of Technology (KIT)	Liquid fuel	Researchers from BASF, Energie Baden-Württemberg AG (EnBW), Heidelberg University and Karlsruhe Institute of Technology (KIT) are seeking to convert CO_2 into a fuel for fuel cells or retrofitted internal combustion engines.	Federal Ministry of Education and Research (BMBF) with more than EUR1 million over two years.		http://www.basf.com/group/pressrelease/P-10-221

APPENDIX M:
EDGE ENVIRONMENT REPORT

edge environment

GLOBAL CARBON CAPTURE AND SEQUESTRATION INSTITUTE
LIFE CYCLE ASSESSMENT OF CARBON DIOXIDE RE-USE TECHNOLOGIES

Edge Environment Pty Ltd

51 Whistler Street
Manly NSW 2095, Australia
P: 02 8962 2644
F: 02 8962 2601
ABN: 941 301 116 16

www: edgeenvironment.com.au

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EXECUTIVE SUMMARY

The Global Carbon Capture and Storage Institute (GCCSI) project had reached the following Phase 1 interim conclusions:

- Enhanced Oil Recovery (EOR) was the technology most able to provide the revenue that might facilitate additional Carbon Capture and Storage (CCS) projects.
- The technologies identified as most promising for accelerating cost reductions for capture are Bauxite Residue Carbonation, Urea Synthesis, Renewable Methanol, and Enhanced Coal Bed Methane (ECBM) recovery.
- The CO_2 reuse technologies that are most likely to accelerate the uptake of alternative forms of CCS include the mineralisation technologies (such as Carbonate Mineralisation, Concrete Curing, Bauxite Residue Carbonation), ECBM and EOR.
- Mineralisation technologies and ECBM are considered to have greater potential in developing countries where the demand for construction materials in the near term is likely to be high and Coal bed methane extraction is already generating significant interest in China with ECBM being a logical means of development.
- EOR and Urea Synthesis are mature technologies already applied on a large scale, yet still have potential for significant growth in the short term.
- Bauxite residue carbonation and renewable methanol are in operation and are close to commercialisation and hence are a potential future market for captured CO_2.
- Carbonate mineralisation, concrete curing and ECBM have the potential to be in commercial operation within 5 years.

The carbon dioxide reuse technologies themselves may consume energy directly or embodied in the equipment used to implement the technology. If these technologies are to show net CO_2 storage benefits it is essential that they store CO_2 at a higher rate than implementing the technology emits CO_2-equivalents (CO_2 plus other Greenhouse Gases emitted – methane, nitrous oxide etc.). This carbon dioxide trade-off can only be assessed using life cycle carbon dioxide (equivalent) assessment.

This report details the further work to conduct a 'scoping' life cycle carbon dioxide equivalent assessment (LCA) for each of the reuse technologies to ascertain its validity as an option for net reductions in greenhouse gas emissions. A 'scoping' LCA is one which approximately models processes and then uses sensitivity analysis to focus on getting accurate data for the 10–20 per cent of parameters that contribute to say 80–90 per cent of the impacts. In this way, quite accurate results can be achieved very cost-effectively. This is very appropriate for new technologies where the operating parameters are still somewhat uncertain.

This project has adopted an unusual approach to life cycle analysis. Conventionally, LCA measures the environmental implications of producing a product or service, but in this project, we are interested in understanding the quantities of product generated in the use of CO_2 as an environmental pollutant. In conventional LCA, we define the product and a functional unit that represents this product. In this case, the functional unit is defined in terms of the use of one tonne of CO_2 in the production of products/services. The goal of this study is:

To approximately assess the lifecycle CO_2-equivalent greenhouse gas emissions associated with the act of reusing CO_2 to produce some product or service, exclusive of any considerations of the permanence of storage in the product or service

The scope of this study is from CO_2 source to product/service point of supply, Adoption of this goal, scope and functional unit enables all of the technologies to be directly compared – all consume one tonne of CO_2 net of any CO_2 equivalents from constructing and operating the processes.

The full details of the methodology are appended.

The report concludes that:

- There is no net benefit of carbon storage for Polypropylene Carbonate production, for Formic Acid production, for Urea Synthesis or for CO_2 Concrete Curing in Canada or for Renewable Methanol production in China.
- Net carbon storage for the different technologies is most for Carbonate Mineralisation, then Algae Cultivation, then Enhanced Coal Bed Methane (ignoring the implications of burning the product), then Enhanced Oil Recovery (ignoring the implications of burning the product), then Bauxite Residue Carbonation, then Enhanced Geothermal.
- The project presumes that gas and oil will be recovered, and that urea, formic acid and polycarbonate polymers will be produced and takes no account of additionality or longevity of storage – these aspects being beyond the project scope.
- The project reveals large variations in
  - operational and total consumptions (0.32 to 5.5tCO_2-e/tCO_2 reused); and
  - embodied carbon in facilities/equipment (ranging from negligible to 6 per cent of total emissions).
- Greenhouse gas emissions from CO_2 capture and pressurisation is a significant factor in several of the technologies assessed. However the emissions vary very significantly depending on the greenhouse intensity of the electricity used for the capture and pressurisation process (ranging from less than 0.2 to over 0.5 tCO_2-e/tCO_2 reused), which can have a proportionally significant impact on the overall results for several technologies.
- Sourcing of low carbon feedstock can significantly alter the total footprint of some technologies. Specifically, the upstream embodied material impacts are significant for Urea Synthesis (68 per cent of the impact from compressed ammonia feedstock), concrete curing (90 per cent of the impact from cement feedstock, primarily due to decarbonation), and Polymer production (94 per cent from propylene oxide feedstock).
- Although data gaps exist in the inventories, sensitivity analysis suggests that none are considered significant enough to alter the overall results from this study.
- Not assessed or included in this study:
  - permanence of the captured CO_2, e.g. whether the captured CO_2 is re-emitted at a later life cycle stage;
  - additionality of the captured CO_2, e.g. whether the absorption of CO_2 would occur in part or completely anyway, such as for example in concrete where CO_2 is gradually recarbonated over time;
  - marginal benefit in terms of mitigated enhanced greenhouse effect against conventional or business as usual technologies;
  - what the consequences are of the CO_2 reuse technologies in other environmental impact categories such as water depletion, emission of toxic pollutants or depletion of resources; and
  - the financial value of these products or services for the extent to which they payback the financial costs of implementing the technologies.

GLOBAL CARBON CAPTURE AND SEQUESTRATION INSTITUTE LIFE CYCLE ASSESSMENT OF CARBON DIOXIDE RE-USE TECHNOLOGIES

1. INTRODUCTION

The Governments of Australia, the United Kingdom, and the United States are collaboratively undertaking a project to identify and demonstrate potential uses for captured carbon dioxide which may generate revenue to offset the cost of carbon dioxide capture (the project). This project will be an early response to the Major Economies Forum Carbon Capture, Use and Storage (CCUS) Technology Action Plan (TAP), which proposes that members:

"…encourage the use of captured CO_2 to generate revenue that can partially offset the cost of CO_2 capture, as a transitional measure to assist the accelerated uptake of CCS."

The project consists of two phases:

- Phase One – a desktop study of the feasibility of a range of options, recommending one or more CO_2 reuse technology projects for evaluation at Phase Two.
- Phase Two – Demonstration of the CO_2 reuse technology projects identified from the phase one feasibility study.

This project has been sponsored by the Global CCS Institute and contributes to the first phase of the project.

The objective of Phase One of this project is to determine the financial value of products and services arising from the use of one tonne of CO_2. However, the processes used to store the CO_2 themselves cause the emission of CO_2 and other greenhouse gasses both embodied in the materials used to construct and for the operation of the facilities and processes used. This results in a consequential CO_2-equivalent (CO_2 plus Global Warming Potential equivalents for other greenhouse gasses emitted) burden that must be subtracted from the tonne of CO_2 saved to understand the real net saving.

The technique of 'Scoping LCA' is used to approximately estimate and assess the consequential greenhouse gas emissions to construct and operate the facilities and processes used by Phase One project technologies. It should be noted that the scope of Phase One does not consider whether the reuse technologies investigated result in a long-term additional storage or sequestration of CO_2 – this is outside of the scope of this work.

2. OBJECTIVE

To undertake a scoping Life Cycle CO_2-equivalent Assessment of each of the Phase 1 CO_2 reuse technologies.

3. METHODOLOGY

The LCA methodology adopted for this project was the subject of an earlier stand-alone report. And this is reproduced in Appendix 1. A 'Scoping LCA' is one based only on key data with many approximate estimates for minor data items coupled to sensitivity analysis. The sensitivity analysis identifies whether any of the approximate data items are a significant contribution to the final results. Where any data item proves to significantly affect final results, this data item is researched more fully until all of the most significant parameters are accurate to give final results that are probably accurate within ± 10 per cent. Within a 'Scoping LCA' there is a small risk that a major parameter might have been overlooked. Edge Environment are highly experienced in this technique and this should mitigate this risk. Edge Environment also use both mass balance and thermodynamic consistency checks to validate their data and assumptions.

4. PROJECTS AND INVENTORY RESULTS

The process diagrams and boundaries illustrating the physical scope of each of the technologies are shown in this section. The physical scope boundary identifies the processes that transform a tonne of CO_2 from its starting form (typically in a flue gas) to its final form as a useful product or service.

Some arrows crossing/entering the boundary indicate input materials, resources, energy sources, products, water that flow into the processes operating inside the boundary. For these upstream inputs, the quantities consumed are modelled in the SimaPro LCA software, linking to life cycle data which tracks upstream back to the origin of primary resources in nature. This tracking through all of the processes used to generate these materials/services/resources accumulates data for the CO_2-equivalent emissions associated with these upstream processes. This data is described as cradle to site (the process site as far as this can be defined) data.

Other arrows crossing/leaving the boundary indicate products, co-products, wastes and pollution generated by the processes inside the boundary. All of the products and co-products contribute to the financial return arising from the CO_2 reuse technologies. All of the wastes and pollution are accounted as environmental burdens from the process. The quantities of wastes and pollution generated are modelled in the SimaPro LCA software for their downstream implications for treatment, possible recycling and disposal of wastes as appropriate (including any emissions from landfill operations that these wastes may contribute to). In some cases – e.g. the emissions to air may directly contribute as greenhouse gases and in others there may be an indirect contribution (e.g. landfill of putrescible wastes may cause methane emissions from landfill operations).

The scope of these LCA's is limited to the point at which the products and co-products are produced and have financial value and DOES NOT extend over the life of use of the products/services. If the scope were to extend over the life of the product/service, then:

- the results would not be consistent with the financial value of the products/services; and
- the results would reveal no net capture of CO_2 for a number of the technologies (e.g. Urea production as a fertiliser releases its CO_2 burden in-use).

Many of the processes are preceded by a CO_2 capture and pressurisation process and this is developed as a modular sub-process (4.12) which is then appropriately (for pressure) embedded into each of the technology processes that use this module. The processes are designated, with the corresponding inventory results for materials, resources, services crossing the boundary as follows:

Section 4.1	Enhanced Oil Recovery (USA)
Section 4.2	Bauxite Residue Carbonation (Western Australia)
Section 4.3	Urea Synthesis (China)
Section 4.4	Enhanced Geothermal Systems (Eastern Australia)
Section 4.5	Enhanced Coal Bed Methane (China)
Section 4.6	Formic Acid Production (South Korea)
Section 4.7	Renewable Methanol (Iceland, captive geothermal energy)
Section 4.8	Carbon Dioxide Concrete Curing (Canada)
Section 4.9	Algae Cultivation (Eastern Australia)
Section 4.10	Carbonate Mineralisation (Eastern Australia)
Section 4.11	Polymer Production (USA)
Section 4.12	Standard Capture Module (sub-process in several of the above technologies)

4.1 ENHANCED OIL RECOVERY (USA)

Figure 1 Enhanced Oil Recovery process diagram

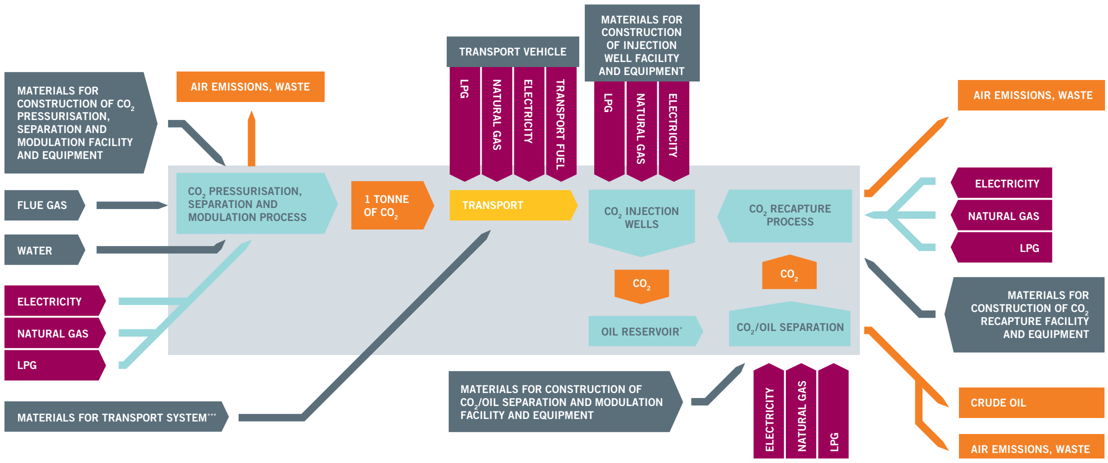


Table 1 Enhanced Oil Recovery inventory.

Scoping LCA Inventory For 1 tonne of Carbon Dioxide Stored			
Equipment/Facilities			**Process**
input	8.06E-04 t	API 5L X70	CO_2 Transport
input	1.60E-06 t	Pipeline Booster Pump	CO_2 Transport
input	2.00E-07 p	Booster Pump Motor 750kW	CO_2 Transport
input	1.60E-06 t	Structural Steel at Booster Station	CO_2 Transport
input	4.00E-06 t	Concrete at Booster Station	CO_2 Transport
Operating Consumption			
input	1 t	CO_2 at 200bar pressure	CO_2 capture module - USA
	5.00E+06 average total amount of captured CO_2 transported over the life of the CO_2 piping transport system		
Equipment/Facilities			**Process**
input	2.9E-04 t	Steel, low alloy	CO_2 Injection Wells
input	1.4E-04 t	Steel, high alloy	CO_2 Injection Wells
input	1.3E-04 t	Cement for wells	CO_2 Injection Wells
input	32 MJ	Diesel	CO_2 Injection Wells
input	3.3E-05 t	Bentonite	CO_2 Injection Wells
input	2.9E-05 t	Inorganic Chemicals	CO_2 Injection Wells
input	5.5E-05 t	Starch	CO_2 Injection Wells
input	2.3E-05 t	Chalk	CO_2 Injection Wells
input	2.9E-03 t	Water	CO_2 Injection Wells
input	1.0E-03 t	Steel, low alloy	Production Wells, apportioned between EOR and conventional oil recovery
input	5.1E-04 t	Steel, high alloy	Production Wells, apportioned between EOR and conventional oil recovery
input	4.7E-04 t	Cement for wells	Production Wells, apportioned between EOR and conventional oil recovery
input	1.1E+02 MJ	Diesel	Production Wells, apportioned between EOR and conventional oil recovery
input	1.2E-04 t	Bentonite	Production Wells, apportioned between EOR and conventional oil recovery
input	1.0E-04 t	Inorganic Chemicals	Production Wells, apportioned between EOR and conventional oil recovery
input	1.9E-04 t	Starch	Production Wells, apportioned between EOR and conventional oil recovery
input	8.2E-05 t	Chalk	Production Wells, apportioned between EOR and conventional oil recovery
input	1.0E-02 t	Water	Production Wells, apportioned between EOR and conventional oil recovery
Operation			
Output	1.70E+07 **t**	**Oil**	Oil collected over the life of the injection well facilities and injection well equipment
Equipment/Facilities			
input	2.2E-05 t	Low alloy steel	Tanks - CO_2/Oil Separation Process
input	4.5E-05 t	concrete	Tank foundation - CO_2/Oil Separation Process
input	1.9E-06	Low alloy steel	Allowance for other Separation Vessels/Treaters - CO_2/Oil Separation Process
input	3.0E-06 t	Low alloy steel and cast iron	Reinjection compressor - CO_2/Oil Separation Process
input	5.6E-08 p	14MW motor	Reinjection compressor motor - CO_2/Oil Separation Process
input	4.9E-07 t	Low alloy steel and cast iron	LP Vent Gas Compressor - CO_2/Oil Separation Process
input	5.6E-08 p	Motor: 250kW	LP Vent Gas Compressor - CO_2/Oil Separation Process
input	1.4E-05 t	Concrete	Equipment foundations - CO_2/Oil Separation Process
input	2.2E-05 t	Low alloy steel	Pipework allowance - CO_2/Oil Separation Process
input	2.2E-05 t	Low alloy steel	Additional Structural steel allowance - CO_2/Oil Separation Process
input	8.9E-05	Concrete	Additional concrete allowance - CO_2/Oil Separation Process
Output	1.8E+07 t	CO_2	CO_2 Separated over the life of the CO_2/Oil Separation Facilities and Equipment
Output	1.7E+07 t	Oil	Oil Separated over the life of the CO_2/Oil Separation Facilities and Equipment
Operation			
Input	0.04 MWh	Electricity (USA)	Pipeline booster compressor
input	0.118 MWh	Electricity (Canada)	Recompression Energy
input	28 MJ	Oil Heater Energy:	
	Main waste is from a gas flare. Water and the majority of CO_2 are re-injected.		
Output	4.87E-02 t	CO_2	including from combustion of oil vapor
	3.00E+07 t CO_2 stored over life		

4.2 BAUXITE RESIDUE CARBONATION (WESTERN AUSTRALIA)

Figure 2 Bauxite Residue Carbonation process diagram

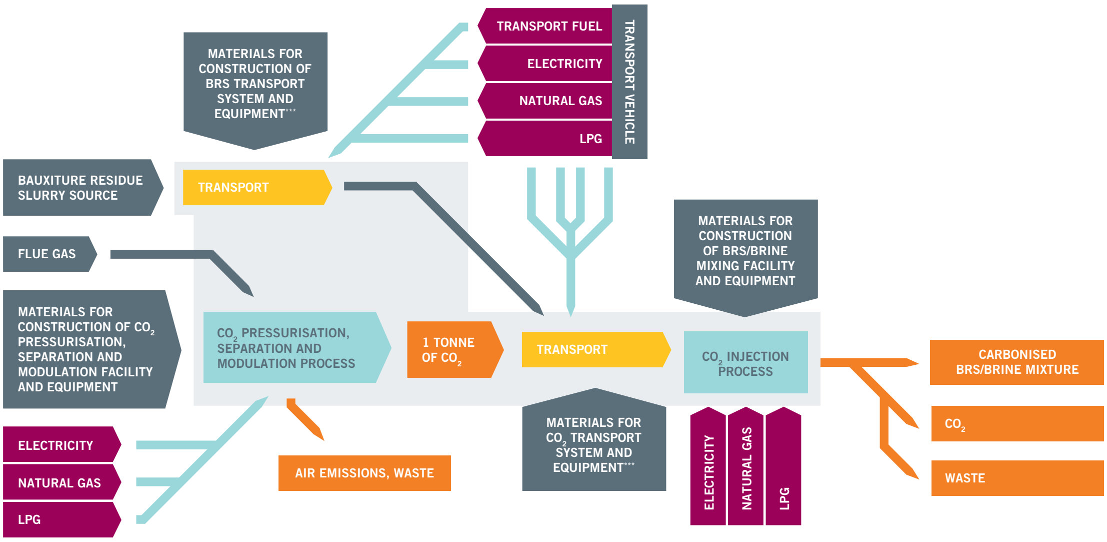


Table 2 Bauxite Residue Carbonation inventory.

Scoping LCA Inventory For 1 tonne of Carbon Dioxide Stored			
Equipment/Facilities			Process
input	3.1E-05 t	Welded steel pipeline	CO2 pipeline transport
input	2.4E-05 t	Concrete anchor blocks	CO2 pipeline transport
input	1.4E-06 t	Steel connectors	CO2 pipeline transport
input	1.7E-05 t	Mild steel	CO2 Injection process
input	1.0E-04 t	Foundation concrete	CO2 Injection process
input	4.4E-06 t	Contactor Vessel	CO2 Injection process
input	4.3E-06 t	Pumps	CO2 Injection process
input	1.4E-06 p	Motors 300kW	CO2 Injection process
input	4.3E-06 t	Piping welded steel	CO2 Injection process
Operation			Process
input	28.57 t	Bauxite Residue Slurry	Bauxite Residue Slurry transport
input	1 t	CO2 at 200bar pressure	CO2 capture module Western Australia 200bar
input	24.7 kWh	Electricity	CO2 Injection process
output	28.6 t	Residue slurry	CO2 Injection process
	1.4E+06 t CO2 stored over life		

4.3 UREA SYNTHESIS (CHINA)

Figure 3 Urea Synthesis process diagram

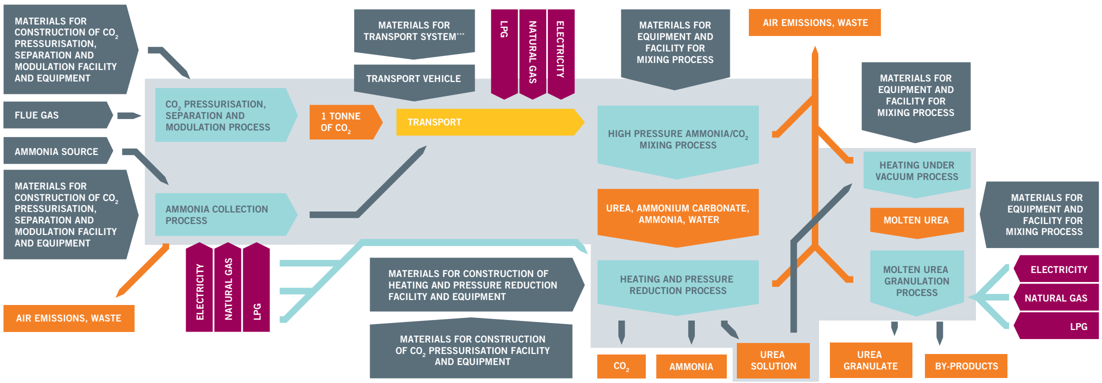


Table 3 Urea Synthesis inventory.

For 1 tonne of CO2 applied to Urea Synthesis				
Equipment/Facilities				**Process**
input	3.1E-05	t	Welded steel pipeline	CO2 pipeline transport
input	2.4E-05	t	Concrete anchor blocks	CO2 pipeline transport
input	1.4E-06	t	Steel connectors	CO2 pipeline transport
input	1.7E-05	t	Mild steel	CO2 Injection process
input	1.0E-04	t	Foundation concrete	CO2 Injection process
input	4.4E-06	t	Contactor Vessel	CO2 Injection process
input	4.3E-06	t	Pumps	CO2 Injection process
input	1.4E-06	p	Motors 300kW	CO2 Injection process
input	4.3E-06	t	Piping welded steel	CO2 Injection process
Operation				**Process**
input	**1**	t	CO2 at 200bar pressure	CO2 capture module China 200bar (China)
input	24.7	kWh	Electricity	CO2 Injection process
	1.4E+06	t	CO2 transported over life	
Equipment/Facilities				**Process**
input	Considered negligible			Ammonia Collection
Operating Inputs				**Process**
input	0.77	t	Ammonia at 175bar	Ammonia Collection
input	4.5	kWh	Electricity (China)	Pumping to 24bar
Equipment/Facilities				**Process**
input			Material inventory is considered negligible	Urea production
Operating inputs				**Process**
input	6.9	kg	Urea formaldehyde (UF85)	Urea production
input	50	l	Water	Urea production
input	76.7	kWh	Electricity (including granulator)	Urea production
input	3509	MJ	Nat Gas (90% eff boiler assumed)	Urea production
input	182	MJ	Nat Gas for low pressure steam	Urea production
Operating outputs				
output	50	l	Water but recycled so assume just make-up	Urea production
output	0.34	kg	Ammonia waste	Urea production
output	0.34	kg	Urea dust	Urea production
output	0.0034	kg	Ammonia in wastewater effluent	Urea production
output	0.0007	kg	Urea in wastewater effluent	Urea production
output	50	l	Effluent water - contaminated	Urea production
output	1.37	t	Urea product	Urea production

4.4 ENHANCED GEOTHERMAL SYSTEMS (EASTERN AUSTRALIA)

Figure 4 Enhanced Geothermal process diagram

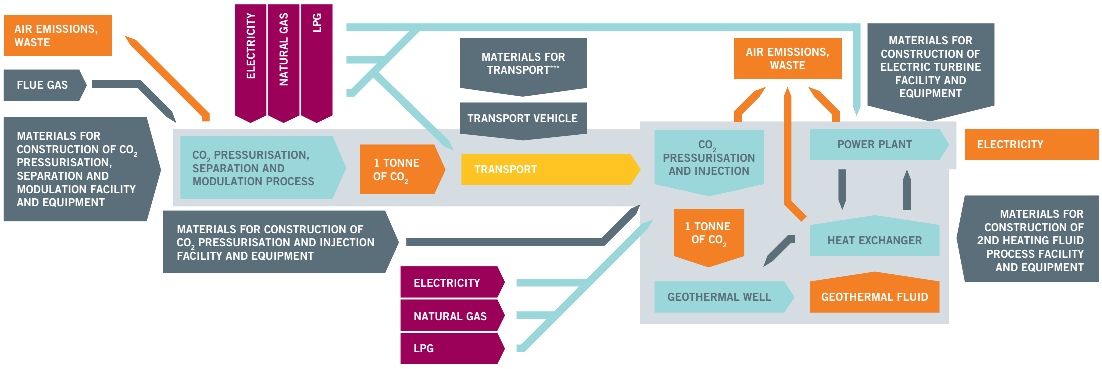


Table 4 Enhanced Geothermal inventory.

For 1 tonne of CO2 applied to Enhanced Geothermal Systems				
Equipment/Facilities				**Process**
input	1.1E-03	t	High Alloy steel pipeline	CO2 Pipeline Transport
input	2.7E-07	t	Intermediate Compressor mass steel as	CO2 Pipeline Transport
input	1.3E-07	t	Intermediate Compressor Turbine mass	CO2 Pipeline Transport
input	5.4E-07	t	Compressor station other steel	CO2 Pipeline Transport
input	1.6E-06	t	Concrete Foundations	CO2 Pipeline Transport
Operating Consumption				**Process**
input	108	MJ	Natural gas	CO2 Pipeline Transport
input	**1**	t	CO2 at 200bar pressure	CO2 capture module
	372000000	t	CO2 transported over life	CO2 Pipeline Transport
Equipment/Facilities				**Process**
input	5.4E-07	t	Compressor steel (excl motor)	CO2 Pressurisation and Injection
input	2.7E-09	p	Electric Motor 55MW	CO2 Pressurisation and Injection
input	5.4E-07	t	Compressor station other steel	CO2 Pressurisation and Injection
input	1.6E-06	t	Concrete Foundations	CO2 Pressurisation and Injection
Operating Consumption				**Process**
input	0.02	MWh	Electricity (need grid)	CO2 Pressurisation and Injection
	372000000	t	CO2 pressurised and injected over life	CO2 Pressurisation and Injection
Equipment/Facilities				**Process**
Surface Plant:				
input	2.1E-05	t	Steel, high alloy	Electric Turbine (incl of 2nd heating process)
input	1.4E-04	t	Steel low alloy	Electric Turbine (incl of 2nd heating process)
input	3.6E-06	t	Copper	Electric Turbine (incl of 2nd heating process)
input	6.6E-05	t	Concrete	Electric Turbine (incl of 2nd heating process)
Deep Wells:				Electric Turbine (incl of 2nd heating process)
input	3.3E-04	t	Steel, low alloy	Electric Turbine (incl of 2nd heating process)
input	1.6E-04	t	Steel, high alloy	Electric Turbine (incl of 2nd heating process)
input	1.5E-04	t	Cement for wells	Electric Turbine (incl of 2nd heating process)
input	36.3	MJ	Diesel	Electric Turbine (incl of 2nd heating process)
input	3.7E-05	t	Bentonite	Electric Turbine (incl of 2nd heating process)
input	3.2E-05	t	Inorganic Chemicals	Electric Turbine (incl of 2nd heating process)
input	6.2E-05	t	Starch	Electric Turbine (incl of 2nd heating process)
input	2.6E-05	t	Chalk	Electric Turbine (incl of 2nd heating process)
input	3.2E-03	t	Water	Electric Turbine (incl of 2nd heating process)
Operating Output				**Process**
output	1	MWh	Electricity generated (Fenton Hill US)	Electric Turbine (incl of 2nd heating process)
	372000000	MWh	Electricity generated over life or CO2 stored over life Assuming same as CO2 pressurised and injected	

4.5 ENHANCED COAL BED METHANE (CHINA)

Figure 5 ECBM process diagram

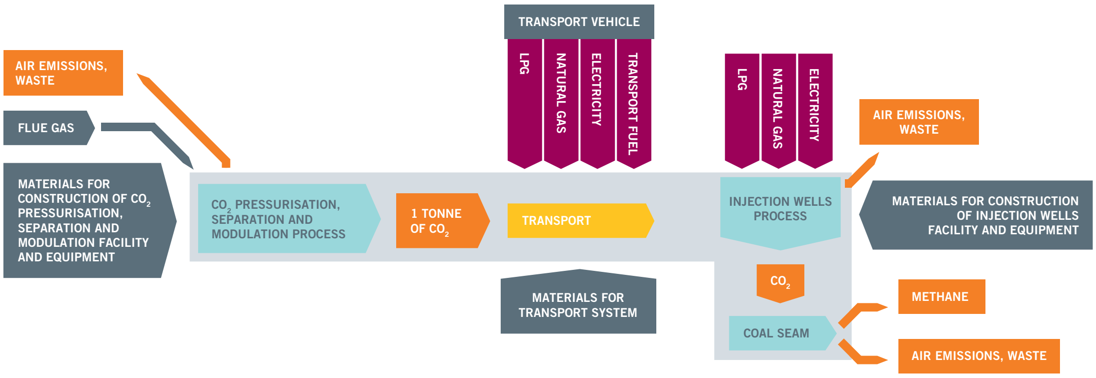


Table 5 ECBM inventory.

For 1 tonne of CO2 applied to Enhanced Coal Bed Methane				
Equipment/Facilities				**Process**
input	3.2E-04	t	Low Alloy steel pipeline	CO2 Pipeline Transport
Operating Consumption				**Process**
input	108	MJ	Natural gas	CO2 Pipeline Transport
input	**1**	t	CO2 at 150bar pressure	CO2 capture module China
	10000000	t	CO2 transported over life	CO2 Pipeline Transport
Equipment/Facilities (15% allocation of production wells and 100% allocation of injection wells to ECBM)				**Process**
	Surface work:			
input	1.3E-06	t	HDPE Surface pipework	CO2 Injection wells - surface
input	3.9E-06	t	Steel in equipment and structural steel	CO2 Injection wells - surface
input	4.8E-06	t	Concrete foundations	CO2 Injection wells - surface
	Wells:			
input	1.8E-04	t	Steel, low alloy	CO2 Injection wells
input	8.8E-05	t	Steel, high alloy	CO2 Injection wells
input	8.0E-05	t	Cement for wells	CO2 Injection wells
input	19.4	MJ	Diesel	CO2 Injection wells
input	2.0E-05	t	Bentonite	CO2 Injection wells
input	1.7E-05	t	Inorganic Chemicals	CO2 Injection wells
input	3.3E-05	t	Starch	CO2 Injection wells
input	1.4E-05	t	Chalk	CO2 Injection wells
input	1.7E-03	t	Water	CO2 Injection wells
	Decomissioning:			CO2 Injection wells
input	2.3E-04	t	Gravel	CO2 Injection wells
input	2.2E-05	t	Cement	CO2 Injection wells
Operating Consumption/Output				**Process**
input	0.02	MWh	Electricity for water treatment plant (Ch	CO2 Pressurisation and Injection
input	2.53	kWh	Electricity (China)	CO2 Injection wells
output	0.122	t	Methane	CO2 Injection wells
output	0.55	t	Waste water	CO2 Injection wells
	10000000	t	CO2 pressurised and injected over life	CO2 Pressurisation and Injection

4.6 FORMIC ACID PRODUCTION (SOUTH KOREA)

Figure 6 Formic Acid Production process diagram

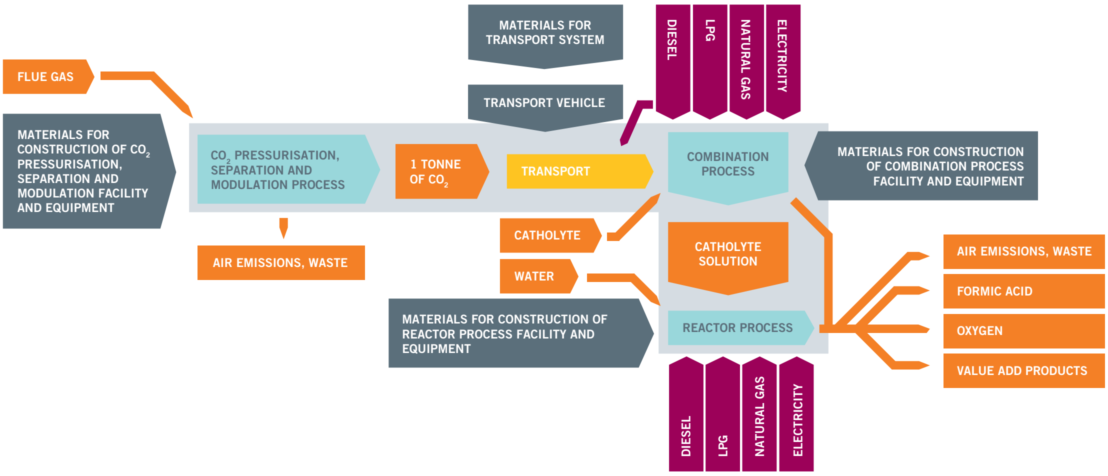


Table 6 Formic Acid Production inventory.

For 1 tonne of CO2 applied to Formic Acid Production			
Equipment/Facilities			**Process**
input	0.0003232 t	Low Alloy steel pipeline	CO2 Pipeline Transport
Operating Consumption			**Process**
input	108 MJ	Natural gas	CO2 Pipeline Transport
input	**1** t	CO2 at 200bar pressure	CO2 capture module South Korea)
	10000000 t	CO2 transported over life	CO2 Pipeline Transport
Equipment/Facilities			**Process**
	PB consider these likely to be negligible		Electrolytic combination process
Operating Consumption/Output			**Process**
input	8 MWh	Electricity (S Korea)	Electrolytic combination process
input	2.98 t	Water	Electrolytic combination process
input	*negl.*	Anolyte	Electrolytic combination process
input	*negl.*	Catholyte	Electrolytic combination process
input	*negl.*	Reactants	Electrolytic combination process
output	1.05 t	Formic Acid	Electrolytic combination process
output	11.4 kg	Hydrogen co-product	Electrolytic combination process
output	167 kg	Oxygen co-product	Electrolytic combination process
output	250 kg	Water reused	Electrolytic combination process

4.7 RENEWABLE METHANOL (ICELAND)

Figure 7 Renewable Methanol process diagram

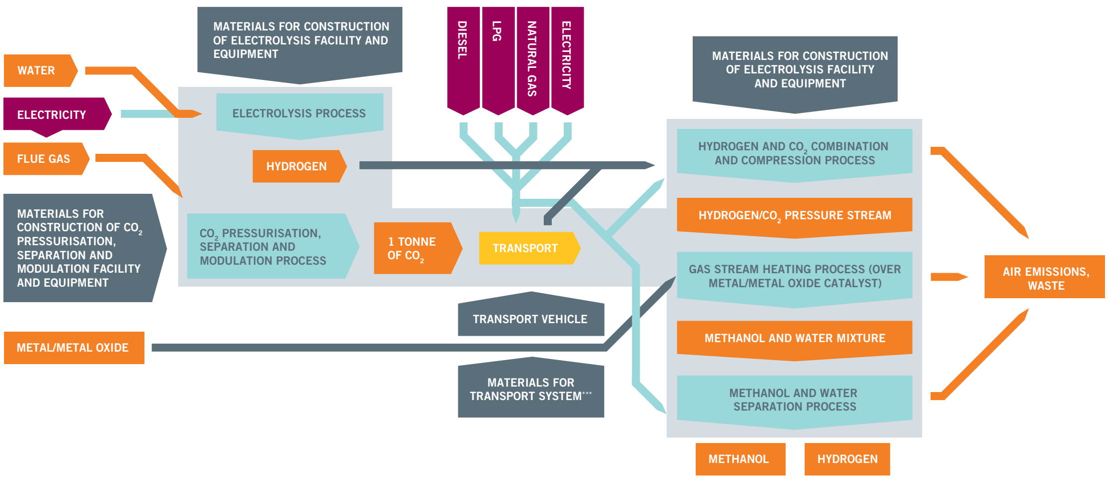


Table 7 Renewable Methanol inventory.

For 1 tonne of CO2 applied to Renewable Methanol			
Equipment/Facilities			**Process**
input	3.2E-04 t	Low Alloy steel pipeline	CO2 Pipeline Transport
Operating Consumption			**Process**
input	108 MJ	Natural gas	CO2 Pipeline Transport
input	**1** t	CO2 at 100bar pressure	CO2 capture module (Electricity Iceland Geothermal)
	1.0E+07 t	CO2 transported over life	CO2 Pipeline Transport
Equipment/Facilities			**Process**
input	Considered negligible by PB on integrated site		H2/CO2 Combination and Compression
Operating Consumption			**Process**
input	8.3 MWh	Electricity Iceland Geothermal Power St	Electrolysis to produce H2
input	0.328 MWh	Electricity Iceland Geothermal Power St	H2 compression
input	0.859 t	Water	
input	0.2 kWh	Water pumping electricity indonesian Geothermal	
input	negligible	Diesel	Metal oxide transport
input	0.4 kg	Cu/ZnO/Al2O3 Catalyst consumed	Metal Oxide catalyst use
output	0.4 kg	Solid waste catalyst	Metal Oxide catalyst use
Equipment/Facilities			
input		Plant and equip TBA - expected to be minimal	Methanol/Water distilation/heat recovery
Operating Consumption			
input	0.112 MWh	Electricity Iceland Geothermal	Methanol/Water distilation/heat recovery
output	0.041 t	Wastewater - remainder recycled to ele	Methanol/Water distilation/heat recovery
output	727 kg	Methanol product	

4.8 CARBON DIOXIDE CONCRETE CURING (CANADA)

Figure 8 CO_2 Concrete Curing process diagram

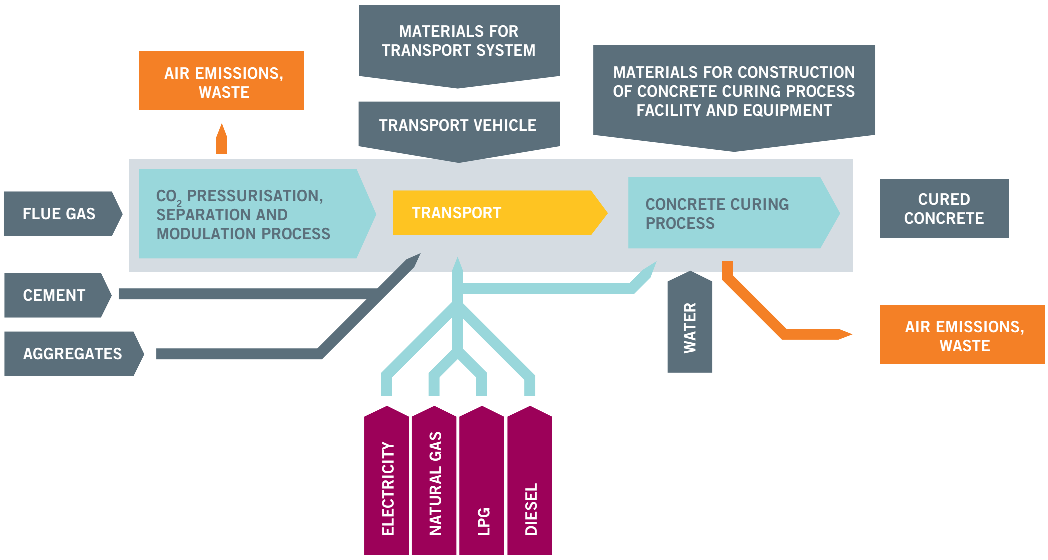


Table 8 CO_2 Concrete Curing inventory.

For 1 tonne of CO2 applied to Concrete Curing			
Equipment/Facilities			**Process**
PB consider these likely to be negligible			Concrete Curing
Operating Consumption/Output			**Process**
input	4680 kg	Water	CO2 Concrete Curing
input	1.84 t	Cement	CO2 Concrete Curing
input	5.10 t	Coarse Aggregate	CO2 Concrete Curing
input	2.70 t	Fine Aggregate	CO2 Concrete Curing
input	1333 MJ	Diesel	CO2 Concrete Curing
input	125 MJ	LPG	CO2 Concrete Curing
input	185 kWh	Electricity (Canada)	CO2 Concrete Curing
input	1 t	CO2 in flue gas	CO2 Concrete Curing
output	2424 kg	Wastewater	CO2 Concrete Curing
output	369 kg	Solid waste (concrete)	CO2 Concrete Curing
output	11.1 t	Cured concrete product	CO2 Concrete Curing

4.9 ALGAE CULTIVATION (EASTERN AUSTRALIA)

Figure 9 Algae Cultivation process diagram

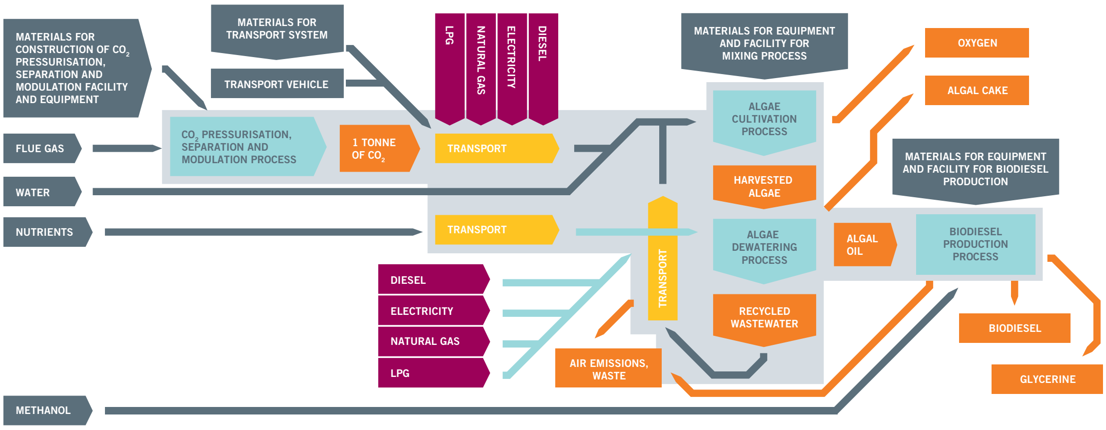


Table 9 Algae Cultivation inventory.

For 1 tonne of CO2 applied to Algal Biofixation

Embodied Energy of Plant and Equipment	**Process**

Embodied energy of biodiesel plant/equipment << 1% of the fossil energy input to biodiesel production (US Department of Agriculture)
Algae Farm: Consider embodied energy negligible compared to operational energy consumption.

Operating Consumption/Output			**Process**
input	0.28 MWh	Electricity	Algae Cultivation & Dewatering Process
input	0.028 MWh	Electricity	Biodiesel Production Process
input	0.95 GJ	Natural Gas	Biodiesel Production Process
input	0.022 t	Methanol	Biodiesel Production Process
input	1.09 t	Waste Water	Algae Cultivation Process
input	0.0048 t	Urea	Algae Cultivation Process
input	0.0033 t	Fertilizer - NPKS 32%/10%/0%/0%	Algae Cultivation Process
output	0.35 t	Algal Cake	
output	0.20 t	Biodiesel	
output	0.022 t	Glycerine	
output	1.09 t	Clean Water	

4.10 CARBONATE MINERALISATION (EASTERN AUSTRALIA)

Figure 10 Carbonate Mineralisation process diagram

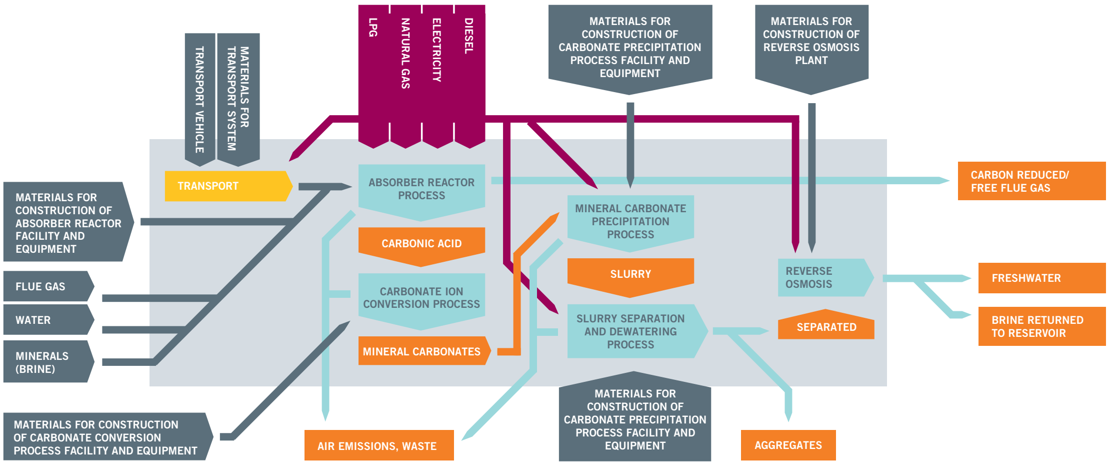


Table 10 Carbonate Mineralisation inventory.

For 1 tonne of CO2 applied to Carbonate Mineralisation

Equipment/Facilities			**Process**
PB is confident the embodied energy of plant and equipment is small compared to operational energy consumption			
Operating Consumption/Output			**Process**
input	9.29 t	Flue Gas	Absorber Reactor Process
input	17.9 t	Brine	Absorber Reactor Process
input	0.5 t	Flyash	Absorber Reactor Process
input	0.12 MWh	Electricity - Flue Gas Transport	Absorber Reactor Process - Flue Gas Transport
input	0.018 MWh	Electricity - Brine pumping power	Absorber Reactor Process - Brine pumping power
input	0.038 MWh	Electricity (Eastern Australia)	Reverse Osmosis
output	9.9 t	Brine returned to reservoir	Reverse Osmosis
output	7.5 t	Freshwater	Slurry Separation and Dewatering Process
output	2.64 t	Mineral carbonate	Slurry Separation and Dewatering Process
output	2.65 t	Aggregates	Slurry Separation and Dewatering Process
output	-0.0012 t	SO2 - Carbon Reduced/Free Flue Gas	Absorber Reactor Process
output	8.29 t	Carbon Reduced/Free Flue Gas	Absorber Reactor Process
output	n/a t	Air Emissions, Waste	Carbonate Ion Conversion Process
output	n/a t	Air Emissions, Waste	Mineral Carbonate Precipitation Process

4.11 POLYMER PRODUCTION (USA)

Figure 11 Polymer Production process diagram

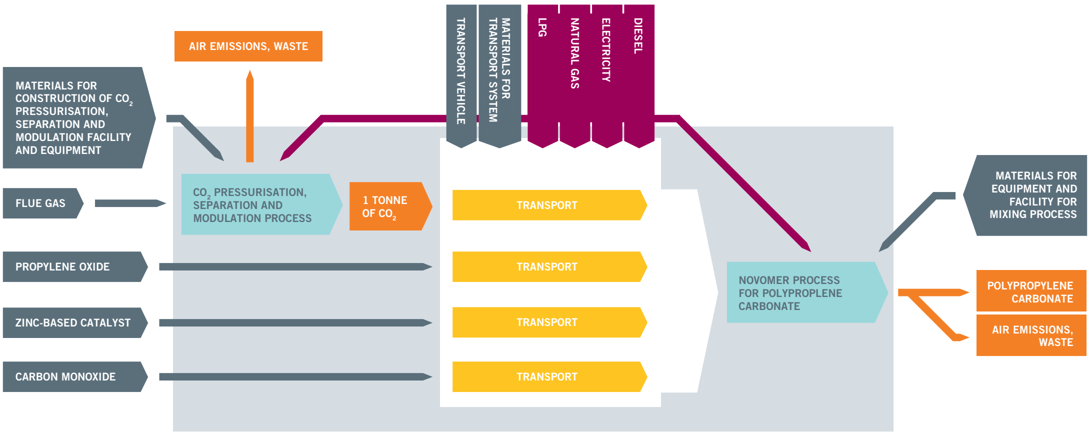


Table 11 Polymer Production inventory.

For 1 tonne of CO2 applied to Polymer Production			
Equipment/Facilities			**Process**
input	3.1E-05 t	Welded steel pipeline	CO2 pipeline transport
input	2.4E-05 t	Concrete anchor blocks	CO2 pipeline transport
input	1.4E-06 t	Steel connectors	CO2 pipeline transport
input	1.7E-05 t	Mild steel	CO2 Injection process
input	1.0E-04 t	Foundation concrete	CO2 Injection process
input	4.4E-06 t	Contactor Vessel	CO2 Injection process
input	4.3E-06 t	Pumps	CO2 Injection process
input	1.4E-06 p	Motors 300kW	CO2 Injection process
input	4.3E-06 t	Piping welded steel	CO2 Injection process
	1400000 t CO2 stored over life		
Equipment/Facilities			**Process**
input	Considered negligible		Mixing Process
Operating Consumption/Output			**Process**
input	1 t	CO2 at 200bar pressure	CO2 capture module (USA)
input	24.7 kWh	Electricity	CO2 Injection process
input	n/a t	Zinc-Based Catalyst Transport	Novomer Process for Polypropylene Carbonate
input	1.32 t	Propylene Oxide	Novomer Process for Polypropylene Carbonate
input	8.9 kWh	Energy inputs to manufacturing process	Novomer Process for Polypropylene Carbonate
output	2.32 t	Polypropylene carbonate	Novomer Process for Polypropylene Carbonate
output	n/a t	Air Emissions, Waste	Novomer Process for Polypropylene Carbonate

4.12 STANDARD CAPTURE MODULE

Figure 12 CO_2 pressurisation and separation process diagram

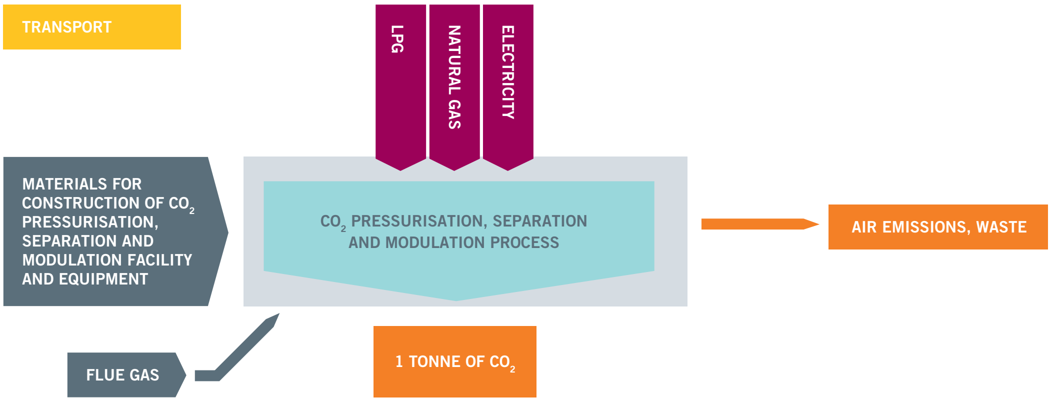


Table 12 CO_2 pressurisation and separation inventory.

For 1 tonne of CO2 Pressurised to 200bar, Separated and Modulated			
Equipment/Facilities			**Process**
input	5.8E-05 t	Mild steel	CO2 Pressurisation, Separation and Modulation
input	1.1E-04 t	Stainless steel	CO2 Pressurisation, Separation and Modulation
input	4.1E-04 t	Concrete	CO2 Pressurisation, Separation and Modulation
input	5.6E-06 p	Motors 4 x 75kW, 2 x 55kW	CO2 Pressurisation, Separation and Modulation
input	1.4E-05 t	Polypropylene	CO2 Pressurisation, Separation and Modulation
input	5.1E-06 p	Compressor Motor 300kW motor	CO2 Pressurisation, Separation and Modulation
input	2.7E-05 t	Compressor	CO2 Pressurisation, Separation and Modulation
Operating Consumption			**Process**
input	3.33 kg	Mono-ethanolamine	CO2 Pressurisation, Separation and Modulation
input	0.93 t	Water	CO2 Pressurisation, Separation and Modulation
input	0.25 MWh	Electricity - capture	CO2 Pressurisation, Separation and Modulation
input	0.115 MWh	Electricity - compression to 100 bar	CO2 Pressurisation, Separation and Modulation
input	0.02 MWh	Added Electricity - compr. to 200 bar	CO2 Pressurisation, Separation and Modulation
output	111 kg	CO2 emissions	CO2 Pressurisation, Separation and Modulation
output	728 g	NOx emissions	CO2 Pressurisation, Separation and Modulation
output	11.1 g	SO2 emissions	CO2 Pressurisation, Separation and Modulation
output	37 g	Particulate emissions	CO2 Pressurisation, Separation and Modulation
output	580 g	NH3 emissions	CO2 Pressurisation, Separation and Modulation
	365000 t	CO2 captured over life of facilities	

5. LIFE CYCLE CARBON DIOXIDE EMISSION RESULTS

The primary data for materials, energy, water and transport inputs and wastes generated and product(s) as outputs come from PB and other project partners. Edge Environment have modelled the inventory flows in the SimaPro LCA database system (v7.1.8), linking to best available and most relevant existing life cycle environmental impacts for upstream and downstream components. Australian life cycle data was used for modelling of equipment and facilities impacts[21]. Fuel combustion emissions (e.g. diesel, natural gas) and Australian national and regional electricity grid emission factors were based on Australian life cycle data. Specific emission factors were not nominated for the Geothermal Power Station used in the renewable methanol production scenario in Iceland. Grid electricity factors for Canada, China, South Korea and USA are based on IEA (2009).

5.1 ENHANCED OIL RECOVERY (USA)

The table below shows the carbon emissions embodied in facilities and equipment, the operational and total emissions per tonne of CO_2 captured.

Table 13 Life cycle carbon dioxide per 1tCO_2 stored with EOR in the USA.

Equipment/Facilities (tCO_2-e) amortised over: • 5,000,000tCO_2 transported over the life of the CO_2 piping transport system; • 17,000,000t Oil collected over the life of the injection well facilities and injection well equipment; • 18,000,000tCO_2 separated over the life of the CO_2/Oil separation facilities and equipment; and • 30,000,000tCO_2 delivered over life through CO_2 injection wells.	0.032
Operation (tCO_2-e)	0.47
TOTAL (tCO_2-e)	0.51

Of the life cycle EOR carbon impacts:

- 94 per cent of the CO_2-e is from operation of the EOR;
- 66 per cent of the CO_2-e is from CO_2 capture and compression to 200bar; and
- 27 per cent of the CO_2-e is from the CO_2/oil separation and CO_2 reinjection process.

21 Australian data was used for modelling of infrastructure impacts for all geographic locations as (1) the Australian average LCA data generally provide conservative embodied greenhouse gas estimates due to the relatively high carbon intensity of average grid electricity and relatively long haulage distances (2) the underlying process quantities are typically internationally comparable as they often are adapted from international (typically European) production and technology data, and (3) refinement of embodied material factors would add little value as the overall result have little sensitivity to the impacts from infrastructure over the projects life.

Figure 13 Overview of CO_2-e emission contribution from EOR operational and equipment/facilities.

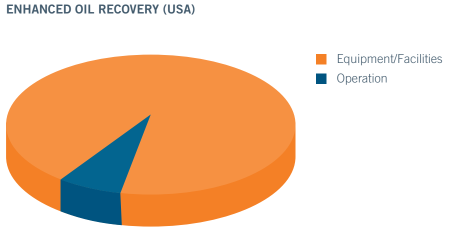
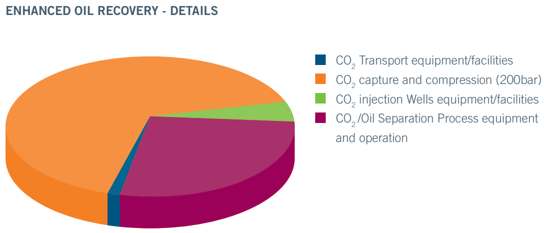


Figure 14 Details of CO_2-e emission contribution from EOR operational and equipment/facilities.



5.2 BAUXITE RESIDUE CARBONATION (WESTERN AUSTRALIA)

The table below show the carbon emissions embodied in facilities and equipment, the operational and total emissions per tonne of CO_2 captured.

Table 14 Life cycle carbon dioxide per 1tCO_2 stored with Bauxite Residue Carbonation in Western Australia.

Equipment/Facilities (tCO_2-e) amortised over 1,400,000tCO_2 stored over life	0.00023
Operation (tCO_2-e)	0.53
TOTAL (tCO_2-e)	0.53

Of the life cycle carbon impacts:

- <0.1 per cent of the CO_2-e is from facilities and equipment;
- 95 per cent of the CO_2-e is from CO_2 capture and compression to 200bar; and
- <5 per cent of the CO_2-e is from electricity for the CO_2 injection process.

Figure 15 Overview of CO_2-e emission contribution from Bauxite Residue Carbonation operational and equipment/facilities.

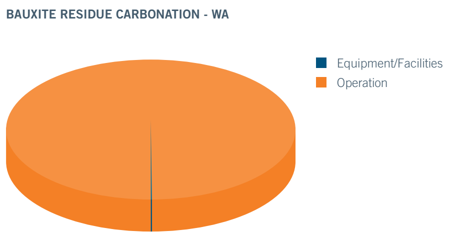
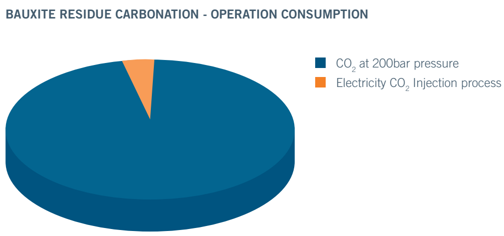


Figure 16 Details of CO_2-e emission contribution from Bauxite Residue Carbonation operation.



5.3 UREA SYNTHESIS (CHINA)

The table below show the carbon emissions embodied in facilities and equipment, the operational and total emissions per tonne of CO_2 captured.

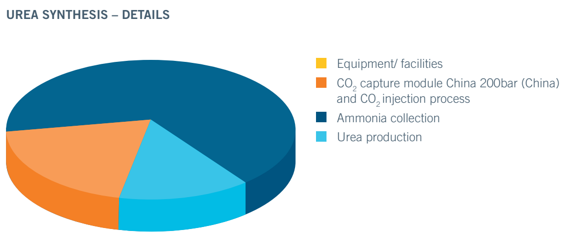
Table 15 Life cycle carbon dioxide per $1tCO_2$ stored with Urea Synthesis in China.

Equipment/Facilities (tCO_2-e) amortised over 1,400,000tCO_2 stored over life	0.00018
Operation (tCO_2-e)	2.27
TOTAL (tCO_2-e)	2.27

Of the life cycle carbon impacts:

- 68 per cent is embodied in from the production and compression of ammonia at 175bar;
- 19 per cent is from the CO_2 capture and compression to 200bar;
- 13 per cent is embodied from the urea production; and
- Embodied impacts of plant and equipment is considered negligible.

Figure 17 Details of CO_2-e emission contribution for Urea Synthesis.



5.4 ENHANCED GEOTHERMAL SYSTEMS (EASTERN AUSTRALIA)

The table below show the carbon emissions embodied in facilities and equipment, the operational and total emissions per tonne of CO_2 captured.

Table 16 Life cycle carbon dioxide per 1tCO_2 stored with Enhanced Geothermal Systems in Eastern Australia.

Equipment/Facilities (tCO_2-e) amortised over 372,000,000tCO_2 transported, pressurised and injected over life	0.023
Operation (tCO_2-e)	0.56
TOTAL (tCO_2-e)	0.58

Of the life cycle carbon impacts:

- 96 per cent for capturing, compressing and injecting CO_2 at 200bar pressure;
- 3 per cent for steel, concrete and compressors in CO_2 pipeline transport, of which 99.99 per cent is embodied in the 407,000 tonne high alloy steel pipeline; and
- 1 per cent embodied in the electric turbine surface plant and deep well.

Figure 18 Overview of CO_2-e emission contribution from Enhanced Geothermal Systems operational and equipment/facilities.

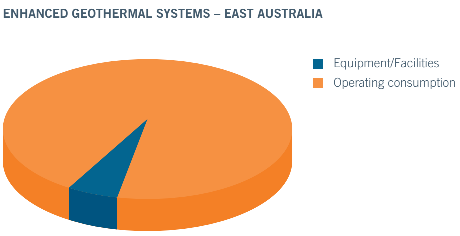
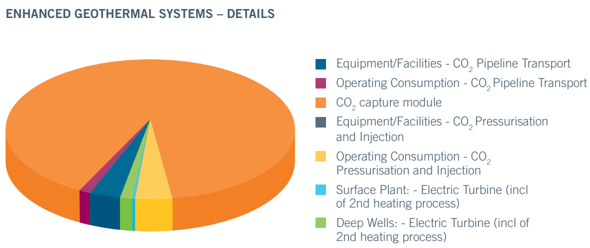


Figure 19 Details of CO_2-e emission contribution for Enhanced Geothermal Systems.



5.5 ENHANCED COAL BED METHANE (CHINA)

The table below show the carbon emissions embodied in facilities and equipment, the operational and total emissions per tonne of CO_2 captured.

Table 17 Life cycle carbon dioxide per 1tCO_2 stored with ECBM in Eastern Australia.

Equipment/Facilities (tCO_2-e) amortised over 10,000,000tCO_2 transported, pressurised and injected over life	0.0043
Operation (tCO_2-e)	0.44
TOTAL (tCO_2-e)	0.44

Of the life cycle carbon impacts:

- 99 per cent is from operational consumptions;
- 94 per cent for capturing, compressing and injecting CO_2 at 150bar pressure; and
- 0.5 per cent is allocated to embodied impacts in surface works, wells and decommissioning.

Figure 20 Overview of CO_2-e emission contribution from ECBM operational and equipment/facilities.

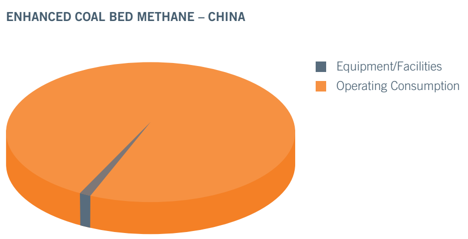
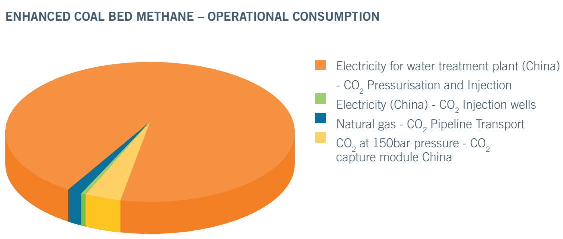


Figure 21 Details of CO_2-e emission contribution for ECBM operational consumption.



5.6 FORMIC ACID PRODUCTION (SOUTH KOREA)

The table below show the carbon emissions embodied in facilities and equipment, the operational and total emissions per tonne of CO_2 captured.

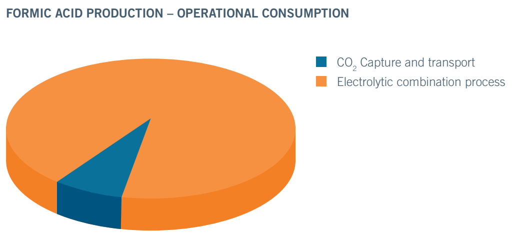
Table 18 Life cycle carbon dioxide per 1tCO_2 stored in Formic Acid production in South Korea.

Equipment/Facilities (tCO_2-e) 10,000,000 tCO_2 transported over life	0.0023
Operation (tCO_2-e)	3.96
TOTAL (tCO_2-e)	3.96

Of the life cycle carbon impacts:

- 93 per cent is from the electrolytic combination process, all from input electricity (8MWh per 1.05t formic acid produced and tonne of CO_2 injected);
- 7 per cent for capturing, compressing and injecting CO_2 at 20bar pressure; and
- embodied impacts of plant and equipment is considered negligible.

Figure 22 Details of CO_2-e emission contribution for Formic Acid production operational consumption.



5.7 RENEWABLE METHANOL (ICELAND)

The table below show the carbon emissions embodied in facilities and equipment, the operational and total emissions per tonne of CO_2 captured.

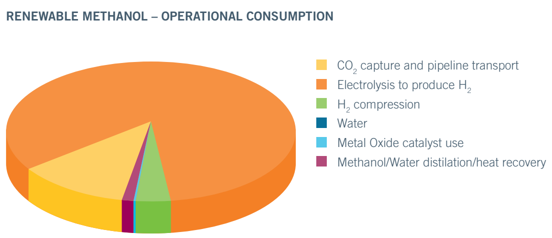
Table 19 Life cycle carbon dioxide per 1tCO_2 stored in Renewable Methanol production in Indonesia.

Equipment/Facilities (tCO_2-e) 10,000,000 tCO_2 transported over life	0.0023
Operation (tCO_2-e)	1.71
TOTAL (tCO_2-e)	1.71

Of the life cycle carbon impacts:

- 99.9 per cent is from operational consumptions;
- 87 per cent is from electrolysis to produce and compression of H_2;
- 11 per cent for capturing, compressing and injecting CO_2 at 100bar pressure; and
- embodied impacts of plant and equipment is considered negligible.

Figure 23 Details of CO_2-e emission contribution for Renewable Methanol production operational consumption.



5.8 CARBON DIOXIDE CONCRETE CURING (CANADA)

The table below show the operational and total carbon emissions per tonne of CO_2 captured

Table 20 Life cycle carbon dioxide per 1tCO_2 stored in Concrete Curing in Canada.

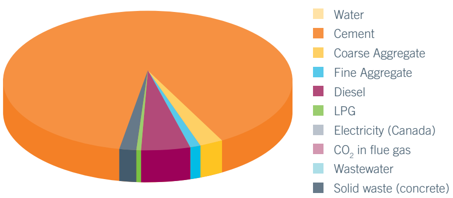
Equipment/Facilities (tCO_2-e) have not been included (assumed negligible)	–
Operation (tCO_2-e)	2.20
TOTAL (tCO_2-e)	2.20

Of the life cycle carbon impacts:

- 90 per cent of the impact is embodied in the 1.8 tonnes of cement for each tonne of CO_2 absorbed from flue gas. It is assumed that 0.4t CO_2 is re-carbonated per tonne of cement (based on 80 per cent re-carbonation of cement with typical 65 per cent CaO mass fraction);
- 5 per cent of the impact is from combustion of diesel;
- 3 per cent is from production and transport of aggregates; and
- embodied impacts of plant and equipment is considered negligible.

Figure 24 Details of CO_2-e emission contribution for CO_2 Concrete Curing.

CO2 CONCRETE CURING – DETAILS



5.9 ALGAE CULTIVATION (EASTERN AUSTRALIA)

The table below show the operational and total carbon emissions per tonne of CO_2 captured

Table 21 Life cycle carbon dioxide per 1tCO_2 stored in Algae Cultivation in Eastern Australia.

Equipment/Facilities (tCO_2-e) have not been included (assumed negligible)	–
Operation (tCO_2-e)	0.42
TOTAL (tCO_2-e)	0.42

Of the life cycle carbon impacts:

- 72 per cent from the algae cultivation & dewatering process;
- 28 per cent biodiesel production process; and
- embodied impacts of plant and equipment is considered negligible.

Figure 25 Details of CO_2-e emission contribution for Algae Cultivation.

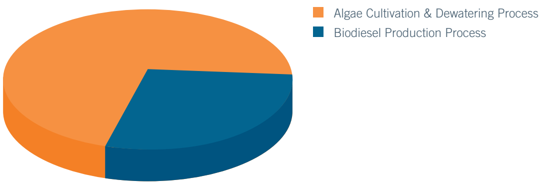
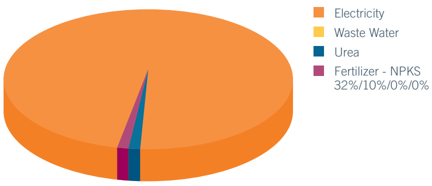


Figure 26 Details of CO_2-e emission contribution for the Algae cultivation Process (72 per cent of total impact).



5.10 CARBONATE MINERALISATION (EASTERN AUSTRALIA)

The table below show the operational and total carbon emissions per tonne of CO_2 captured

Table 22 Life cycle carbon dioxide per 1tCO_2 stored in Carbonate Mineralisation in Eastern Australia.

Equipment/Facilities (tCO_2-e) have not been included (assumed negligible)	–
Operation (tCO_2-e)	0.32
TOTAL (tCO_2-e)	0.32

Of the life cycle carbon impacts:

- 88 per cent of the impact is from the absorber reactor process, of which 48 per cent is embodied in the fly ash (based on economic allocation of emissions from coal fired power station between ash (approx. 1.2 per cent of the value produced) and electricity);
- 12 per cent reverse osmosis, primarily from electricity consumption; and
- embodied impacts of plant and equipment is considered negligible.

Figure 27 Details of CO_2-e emission contribution for Carbonate Mineralisation.

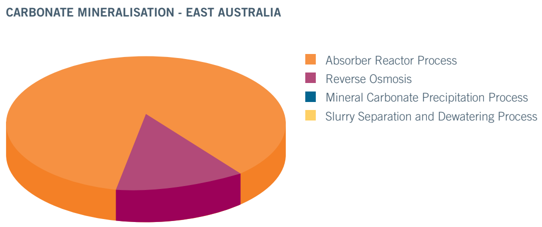
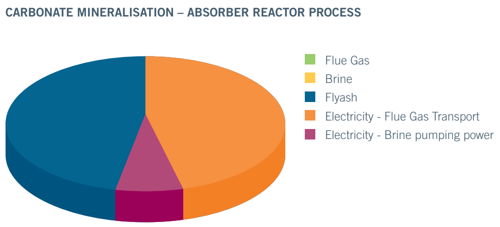


Figure 28 Details of CO_2-e emission contribution for the Carbonate Mineralisation Absorber Reactor Process (88 per cent of total impact).



5.11 POLYMER PRODUCTION (USA)

The table below show the operational and total carbon emissions per tonne of CO_2 captured

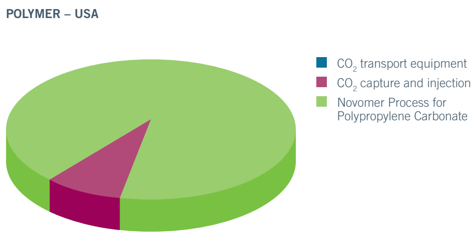
Table 23 Life cycle carbon dioxide per 1tCO_2 stored in Polymer production in the USA.

Equipment/Facilities (tCO_2-e) amortised over 1,400,000tCO_2 stored over life	0.00023
Operation (tCO_2-e)	5.52
TOTAL (tCO_2-e)	5.52

Of the life cycle carbon impacts:

- 94 per cent of the impact is embodied in the propylene oxide feedstock (3.9tCO_2e/t based on European Ecoinvent life cycle data);
- 6 per cent is from the CO_2 capture module; and
- embodied impacts of plant and equipment is considered negligible.

Figure 29 Details of CO_2-e emission contribution for Polymer production.



5.12 STANDARD CAPTURE MODULE

The standard capture module is used in most of the above technology scenarios. The table below shows the greenhouse gas emission for the different locations and pressures used per tonne of CO_2 captured and pressurised

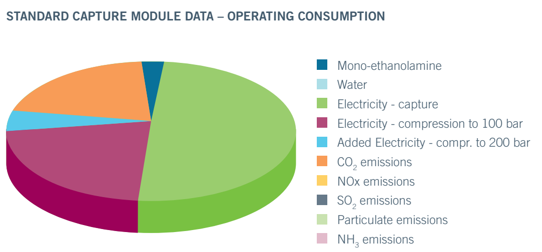
Table 24 Life cycle carbon dioxide per 1tCO_2 captured and pressurised.

Equipment/Facilities (Australia over 365,000tC_{O2} life) (tCO_2-e)	0.001
Operation Australia Average 200bar (tCO_2-e)	0.50
Operation China 200bar (tCO_2-e)	0.42
Operation Eastern Australia 200bar (tCO_2-e)	0.53
Operation Western Australia 200bar (tCO_2-e)	0.51
Operation USA 200bar (tCO_2-e)	0.34
Operation China 150bar (tCO_2-e)	0.41
Operation Svartsengi Geothermal Indonesia 100bar (tCO_2-e)	0.19
Operation South Korea 20bar (tCO_2-e)	0.27

As reference case for process contribution, CO_2 pressurisation using Australian average emission factors for processes, energy consumption and material:

- 76 per cent of the CO_2-e is from electricity consumption for capture and compression (Scope 2);
- 22 per cent of the CO_2-e is from direct CO_2 emissions onsite (Scope 1);
- 2 per cent of the CO_2-e is from production of mono-ethanolamine (Scope 3); and
- 0.2 per cent of the CO_2-e is embodied in equipment/facilities (Scope 3).

Figure 30 Overview of operational CO_2-e emission contribution for CO_2 pressurisation using Australian average production data and emission factors.



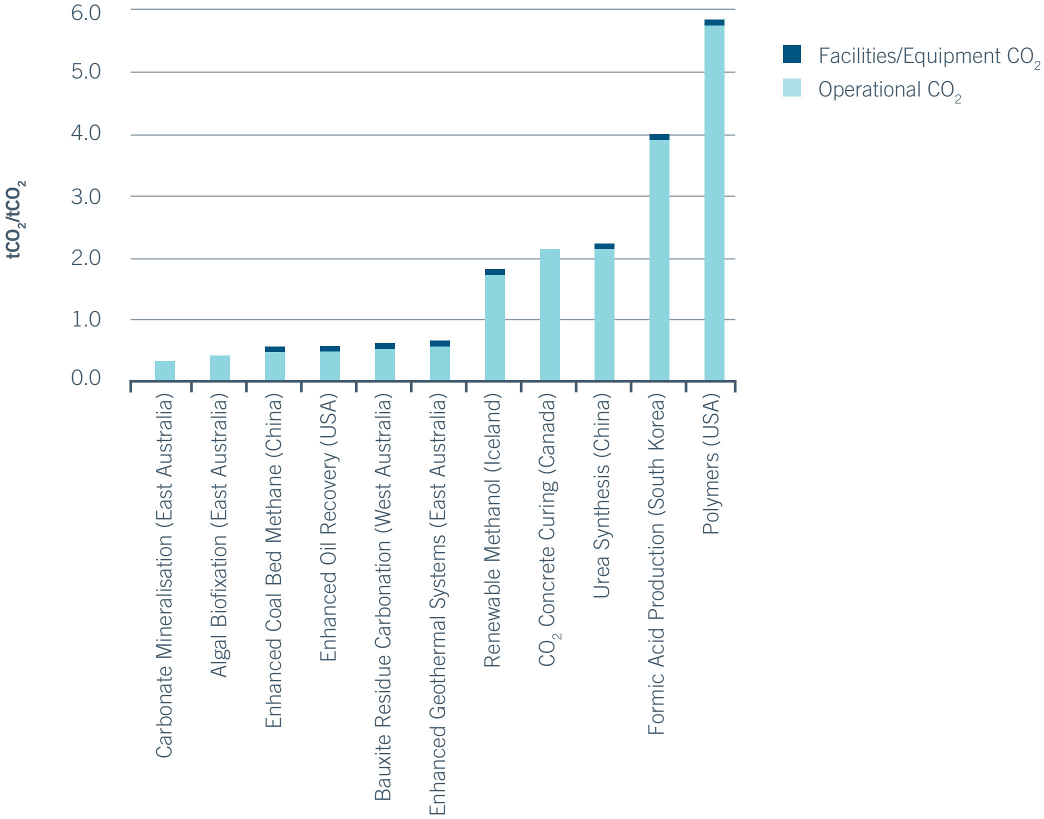
6. SUMMARY

Table 25 summarises the results for each of the technologies and contexts studied. For any of the technologies with a tCO_2-e value greater than one, the technology will in operation omit more greenhouse gas emissions than it will store.

Table 25 Summary of life cycle greenhouse gas emissions and products/outputs per $1tCO_2$ stored.

TECHNOLOGY	TCO_2-E			PRODUCT/OUTPUT
Enhanced Oil Recovery (USA)	0.51	0.57	t	Oil
Bauxite Residue Carbonation (West Australia)	0.53	28.6	t	Residue slurry
Urea Synthesis (China)	2.27	1.37	t	Urea product
Enhanced Geothermal Systems (East Australia)	0.58	1	MWh	Electricity
Enhanced Coal Bed Methane (China)	0.44	0.122	t	Methane
Renewable Methanol (Iceland)	1.71	727	kg	Methanol product
Formic Acid Production (South Korea)	3.96	1.05	t	Formic Acid
		11.4	kg	Hydrogen co-product
		167	kg	Oxygen co-product
CO_2 Concrete Curing (Canada)	2.20	11.1	t	Cured concrete product
Algae Cultivation (East Australia)	0.42	0.35	t	Algal Cake
		0.20	t	Biodiesel
		0.02	t	Glycerine
		1.09	t	Clean Water
Carbonate Mineralisation (East Australia)	0.32	7.50	t	Freshwater
		2.64	t	Mineral carbonate
		2.65	t	Aggregates
Polymers (USA)	5.52	2.32	t	Polypropylene carbonate

Figure 31 CO_2 Storage Summary Graphical presentation



7. CONCLUSIONS

- There is no net benefit of carbon storage for Polypropylene Carbonate production, for Formic Acid production, for Urea Synthesis or for CO_2 Concrete Curing in Canada or for Renewable Methanol production in China.
- Net carbon storage for the different technologies is most for Carbonate Mineralisation, then Algae Cultivation, then Enhanced Coal Bed Methane (ignoring the implications of burning the product), then Enhanced Oil Recovery (ignoring the implications of burning the product), then Bauxite Residue Carbonation, then Enhanced Geothermal.
- The project presumes that gas and oil will be recovered, and that urea, formic acid and polycarbonate polymers will be produced and takes no account of additionality or longevity of storage – these aspects being beyond the project scope.
- The project reveals large variations in
  - operational and total consumptions (0.32 to 5.5tCO_2-e/tCO_2 reused), and
  - embodied carbon in facilities/equipment (negligible in most cases but approximately 5 per cent of total emissions for EOR and Enhanced Geothermal)
- Greenhouse gas emissions from CO_2 capture and pressurisation is a significant factor in several of the technologies assessed. However the emissions vary very significantly depending on the greenhouse intensity of the electricity used for the capture and pressurisation process (ranging from less than 0.2 to over 0.5 tCO_2-e/tCO_2 reused), which can have a proportionally significant impact on the overall results for several technologies.
- Sourcing of low carbon feedstock can significantly alter the total footprint of some technologies. Specifically, the upstream embodied material impacts are significant for Urea Synthesis (68 per cent of the impact from compressed ammonia feedstock), concrete curing (90 per cent of the impact from cement feedstock, primarily due to decarbonation), and Polymer production (94 per cent from propylene oxide feedstock).
- Although data gaps exist in the inventories, sensitivity analysis suggests that none are considered significant enough to alter the overall results from this study.
- Not assessed or included in this study:
  - Permanence of the captured CO_2, e.g. whether the captured CO_2 is re-emitted at a later life cycle stage
  - Additionality of the captured CO_2, e.g. whether the absorption of CO_2 would occur in part or completely anyway, such as for example in concrete where CO_2 is gradually recarbonated over time.
  - Marginal benefit in terms of mitigated enhanced greenhouse effect against conventional or business as usual technologies
  - What the consequences are of the CO_2 reuse technologies in other environmental impact categories such as water depletion, emission of toxic pollutants, ecological diversity or depletion of resources.
  - The financial value of these products or services for the extent to which they payback the financial costs of implementing the technologies.

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