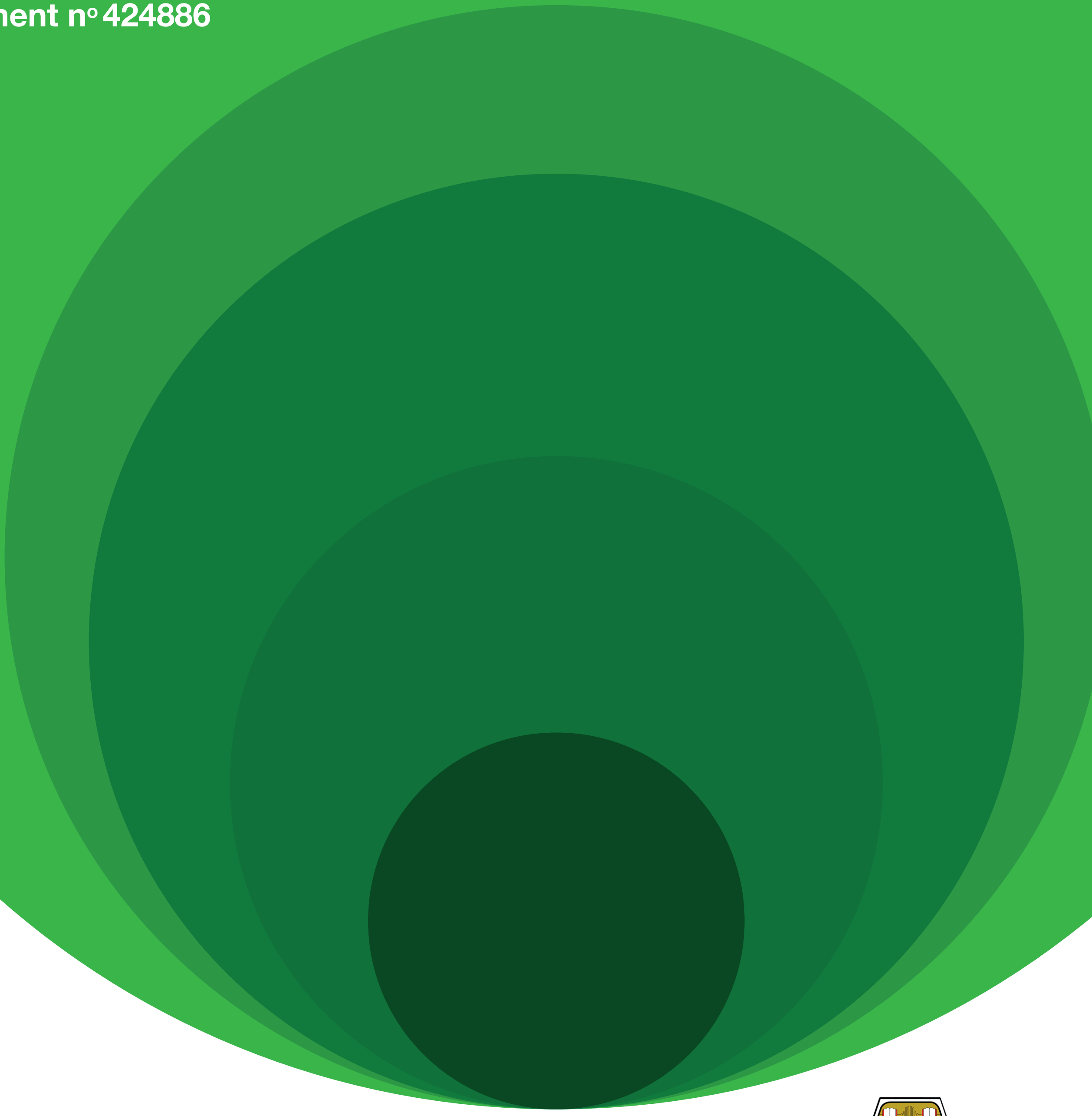
# Actions required to develop a roadmap towards a Carbon Dioxide Utilisation Strategy for Scotland

## June 2016

Grant Agreement nº 424886



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**Cover Image**

The areas of the five full circles on the cover image represent the magnitudes of carbon dioxide ($CO_2$) in tonnes per annum.

- The smallest and darkest circle represents the estimated Scottish Distilling Sector biogenic $CO_2$ capture potential **at 0.5 million tonnes per annum.**
- The next circle up represents an overall estimate of the total Scottish biogenic carbon dioxide capture potential as estimated for the distilling sector and reported for biomass and bioenergy facilities through the SEPA SPRI database **at 1.5 million tonnes per annum.**
- The third circle includes the carbon dioxide capture potential for the Grangemouth region as reported through the SEPA SPRI database **at 3.1 million tonnes per annum.**
- The fourth circle represents the combined volumes of the second and third circles or an estimated carbon dioxide capture potential across Scotland **at 4.3 million tonnes per annum.**
- The area of the largest circle represents the total of Scotland's carbon emissions that are reported through the SEPA SPRI database by all emitters of greater than 10,000 tonnes of $CO_2$ per year. This is **10 million tonnes per annum.**

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The report brings together a team of experts from the $CO_2$ Utilisation and Carbon Capture and Storage sectors.

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# About Scottish Enterprise

Scottish Enterprise is Scotland's main economic development agency and aims to deliver a significant, lasting effect on the Scottish economy. Our role is to help identify and exploit the best opportunities for economic growth. We support ambitious Scottish companies to compete within the global marketplace and help build Scotland's globally competitive sectors. We also work with a range of partners in the public and private sectors to attract new investment to Scotland and to help create a world-class business environment.

# Background to this report

Scottish Enterprise commissioned this report to better understand the required actions in developing a roadmap towards a $CO_2$ utilisation strategy for Scotland. This document provides an overview of $CO_2$ utilisation with respect to opportunities in Scotland and provides recommendations for further steps for Scotland to explore and develop its potential in this area.

As part of the Chemical Sciences Scotland strategy refresh in 2012, Grangemouth was identified as a key chemical manufacturing location, and is described as a 'transformational project' for this sector. This led to a study among Chemical Sciences Scotland, Scottish Enterprise and Falkirk Council, and several key organisations located in the area, the findings of which indicated that the development of Grangemouth by promoting it on the international stage might attract economic benefits as follows:

At a local level, the estimated impact is a net additional 5,116 jobs, with net additional GVA of £462.8m by 2025. Again, around half of the jobs are anticipated to be generated in the chemicals sector[1]. In October 2013, the position changed at Grangemouth with the industrial relations dispute and the threatened closure of the petrochemicals business and the refinery. This dispute highlighted Grangemouth as Scotland's largest industrial location and its importance for and potential impact on the Scottish economy.

Since then a cross-business and public sector team has been working to develop this location to good effect. However, the landscape is changing again and other potential scenarios require consideration.

Simultaneously DECC has developed a roadmap for the Decarbonisation of the Chemical Sciences sector, which Scottish Government has indicated a desire to develop further for Scotland. In addition, Scotland has published challenging emissions targets and has an ambition to develop a Carbon Capture and Storage (CCS) exemplar utilising assets and expertise available in Scotland.

Scottish Enterprise aims to understand:

- how the utilisation of $CO_2$ can provide cross-sectoral economic opportunities in Scotland
- how Scotland can leverage its current and potential future $CO_2$ resources
- how can help to decarbonise the Chemical Sciences sector in particular
- how can help to realise the Grangemouth vision for sustainable high value chemical manufacturing over the longer-term

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[1] 'Falkirk, Grangemouth Framework for Growth '– Roger Tym & Partners, October 2011.

# Foreword: Why should Scotland be interested in $CO_2$ utilisation?

**$CO_2$ Utilisation or Carbon Capture and Utilisation (CCU) holds out the promise of providing economic activity in Scotland by re-using its $CO_2$ as a feedstock to create various products. This economic activity has the potential to help Scotland shift to a lower-carbon, more sustainable and more circular economy through better management and re-use of its carbon, and in particular, by helping Scotland to develop its $CO_2$ resource by giving it a value.**

Humanity is not going to stop using carbon, as it is an intrinsic building block of our society. However, the typical extraction, use of and subsequent emission to the atmosphere of underground sources of carbon (fossil fuels and limestone) has to change, as the risks associated with climate change require that we do. **Scotland is one of the fortunate countries that may be able to generate economic opportunities from the necessary change of its extract, utilise, emit linear relationship with carbon.**

Scotland has one of the longest histories of any country in developing its fossil carbon resources at scale[2]. During the 1850's it was the first country to develop its cannel coal deposits to produce mineral oil, it then switched over to using shale deposits to produce the mineral oil from the 1860's. Technical expertise from Scotland provided an important role in the development of oil industries globally as petroleum came to dominate the supply chain for liquid hydrocarbons. In time, Scotland was able to develop its offshore hydrocarbon resources too. The challenges overcome in the extreme conditions of the North Sea again allowed Scotland to export its technical expertise throughout the oil and gas sector around the world. The manufacturing complex at Grangemouth, one of the UK's largest, is testimony to the long history that Scotland has had, both with its onshore carbon, and the carbon riches of the North Sea.

The historical exploitation of North Sea hydrocarbons provides a future opportunity for Scotland, as the nature and scale of potential geological storage sites for $CO_2$ offshore are well characterised[3]. Scotland's proximity to world class $CO_2$ stores in the North Sea[4] suggests that it is well placed to continue its relationship with fossil carbon over the long-term. As the world transitions to products with lower environmental impacts, it will need access to lower impact feedstocks and fuels to create these products. $CO_2$ Utilisation offers a route to provide the carbon needed for lower impact products (as the carbon is being re-used), but due to the low cost of 'virgin' carbon from fossil fuel sources, there is currently little market pull through. However, in the medium to long-term, if CCS is able to provide the industrial complexes at Grangemouth with a long-term low carbon future that allows the area to become one of Europe's major low carbon manufacturing hubs, then $CO_2$ utilisation is likely to find a role to play here too.

However, the re-use of carbon described as '$CO_2$ utilisation', rather than simply the geological storage of carbon is the main focus of this report. The re-use of fossil carbon before it enters the atmosphere provides the ability to attach more economic activity to the same carbon atom without the level of associated emissions of the typical once through an economic system extract, utilise, and emit type of

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[2] http://www.scottishshale.co.uk/ (online) accessed April 2016

[3] http://www.eti.co.uk/project/strategic-uk-ccs-storage-appraisal/ (online) accessed May 2016

[4] Progressing Development of the UK's Strategic Carbon Dioxide Storage Resource: A Summary of Results from the Strategic UK CO2 Storage Appraisal Project' http://www.eti.co.uk/wp-content/uploads/2016/04/D16-10113ETIS-WP6-Report-Publishable-Summary.pdf (online) accessed May 2016

activity. Re-use of carbon using $CO_2$ utilisation technologies helps shift Scotland to a more circular and sustainable economy, and helps to decouple its economic growth from greenhouse gas emissions. In addition to the re-use of fossil based carbon, the re-use of non-fossil sources such as carbon from energy crops and as a by-product of fermentation in the Food and Drink sector presents Scotland with some unique potential opportunities too.

Scotland's Whisky sector has undergone significant expansion over the last 30 years. This sector produces an historically underutilised by-product in the form of **high purity biogenic**[5] **$CO_2$** throughout the year from the fermentation of malted barley and grains. Certain $CO_2$ utilisation technologies provide the potential to add value to some of this $CO_2$ resource, *e.g.* in the creation of fertiliser, which could provide a valuable carbon loop between the food and drink and agricultural sectors, and reshore the manufacture of inorganic fertiliser to Scotland.

Scotland has significant academic strengths in the carbon sector too[6], that would be active partners in a developing $CO_2$ utilisation sector. A technical section at the end of this report details the work carried out by Interface to explore the academic capacity in Scotland. It finds that due to the cross-cutting nature of many of the research and technology challenges for $CO_2$ utilisation, that a wide range of disciplines are relevant to $CO_2$ utilisation including such areas as catalyst development, biotechnology and process engineering. It also identified other recent initiatives in Scotland that could have some relevance to the development of $CO_2$ utilisation including the business led Scottish Formulation Network and the eight Innovation Centres[7].

Due to the early stage of deployment of many of the technologies of $CO_2$ utilisation at a global level (other than enhanced oil recovery and production of urea), accelerating the deployment of $CO_2$ utilisation within Scotland could be **globally significant**. $CO_2$ utilisation shows promise in certain areas that could be particularly attractive to Scotland and this report recommends various actions that would be helpful in the development of a roadmap to accelerate $CO_2$ utilisation in Scotland.

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[5] from a biological source of carbon rather than a fossil source of carbon, typically biomass created via photosythesis that removes $CO_2$ from the atmosphere

[6] detailed in Appendix 1

[7] http://www.sfc.ac.uk/Priorities/Innovation/FundedInnovationCentres.aspx (online) accessed April 2016

# Executive Summary

Scotland has spent considerable effort investigating the benefits of Carbon Capture and Storage (CCS) and $CO_2$-EOR (Enhanced Oil Recovery) as potential routes to strategically manage its carbon. Both of these routes are of great interest, but require a significant level of public sector investment in infrastructure to develop, as the market signals are not strong enough to provide the necessary investment from the private sector alone. $CO_2$ utilisation offers additional carbon management options by using $CO_2$ as a carbon resource to make products such as $CO_2$-derived fuels, chemical feedstocks, specialist chemicals, inorganic fertiliser and mineralised products. Some of these could make use of, and tie into CCS infrastructure when it is developed, but other processes and products can make use of the $CO_2$ resources that are not likely to connect to CCS infrastructure, as they are either too small or too remote (or both). $CO_2$ utilisation does not need to wait on CCS infrastructure being deployed and can contribute to Scotland's economy without the same level of carbon emissions compared to a fossil fuel business as usual case. It therefore offers additional opportunities for Scotland to decouple its economic activity from its emissions.

However, the potential near-term demand for $CO_2$ utilisation products relative to Scotland's emissions is low, to the extent that $CO_2$ utilisation **SHOULD NOT** be considered a substitute for CCS. The two different carbon management routes have different aims, with different scales of deployment, and are considered to be **complementary**. A difference in storage timelines with regard to material impact on climate change exists between CCS and $CO_2$ Utilisation.

Scotland is fortunate to have several strategic options in terms of carbon management, and in common with CCS and $CO_2$-EOR that have garnered considerable interest, $CO_2$ utilisation is starting to attract interest around the world, notably at a European level. Part of the reason Germany in particular is keen to develop its $CO_2$ utilisation sector is due to its move away from CCS as a carbon management option due to negative public opinion (which is not the case in Scotland). However, additional longer-term reasons that Germany has invested in the development of $CO_2$ utilisation should be of a similar interest to Scotland, and include the broadening of the chemical feedstock supply chain away from fossil-fuels, import substitution of fossil-fuel for certain transport and heating fuels, and to provide a significant dispatchable demand to accommodate excess electrical energy at times of potential oversupply. In 2015, Germany exported 88.2TWh of electrical energy and imported 33.2TWh, and was therefore a net exporter of 56TWh. For comparison, in 2014 Scotland exported 12TWh and imported 0.2TWh, and was therefore a net exporter of 11.8TWh of electricity.

The Grangemouth region is clearly the location for any longer-term strategic aspiration to create a $CO_2$ utilisation hub of scale in Scotland, as it would be an industrial location that would be straightforward to tie into CCS infrastructure (with access to significant volumes of $CO_2$). Grangemouth is also Scotland's largest manufacturing region with access to a deep and broad Chemical Sciences knowledge base and its associated supply chains. As Grangemouth develops its potential as an Industrial Biotechnology cluster, there are also likely to be synergies and industrial symbiosis opportunities that use $CO_2$ to provide additional value.

However, future volume markets for $CO_2$ utilisation products *e.g.* chemical feedstocks or fuels are some way off, as legislative changes would be needed to help provide additional market pull by closing the cost gap between $CO_2$ utilisation products and fossil derived equivalents.

# Key findings from this report

Scotland has:

- a significant source of high quality biogenic $CO_2$ from the distillery and bioenergy sectors
- vibrant $CO_2$ utilisation, hydrogen and CCS academic communities
- a significant renewable energy resource

From Table 4 from Section 5: *Scotland's $CO_2$ resources in tonnes per annum and suggested target uses*

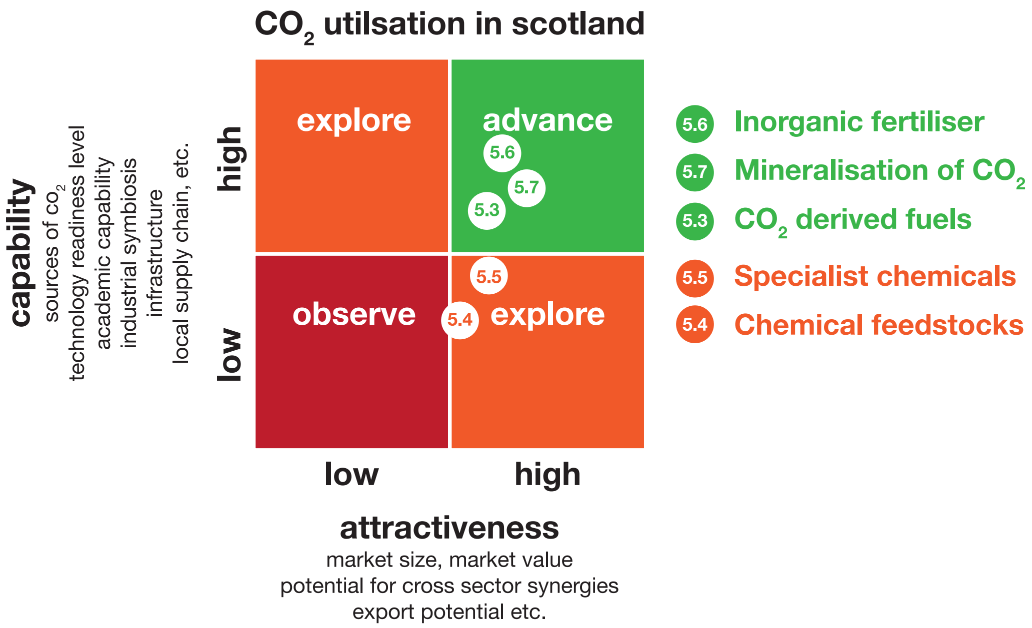
| Type of $CO_2$ resource | Tonnage of $CO_2$ per annum | Could connect to CCS $CO_2$-EOR infrastructure? | Suggested target use for $CO_2$ |
|---|---|---|---|
| The top 12 largest emitters within 50 road miles of Grangemouth | 3.1 million (0.5 million is biomass) | YES | CCS, $CO_2$-EOR, $CO_2$ derived fuels, chemical feedstocks, specialist chemicals |
| Seven bioenergy locations greater than 50 road miles away from Grangemouth | 0.7 million | NO<br>(Tanker option) | $CO_2$ derived fuels, inorganic fertiliser |
| Biogenic fermentation $CO_2$ from distillery sector | 0.5 million | NO<br>(Tanker option) | Inorganic fertiliser |
| Smaller point sources in island, rural and agricultural communities | ? | NO | $CO_2$ derived fuels, inorganic fertiliser |
| Smaller industrial point sources | ? | NO | Mineralised wastes |
| Total | 4.3 million | | |

- There are near-term opportunities for Scotland to consider for $CO_2$ utilisation, the two of greatest interest are the production of inorganic fertiliser using $CO_2$ as a feedstock, and the mineralisation of certain industrial waste streams using $CO_2$. Both of these have UK based technology providers that have already built pilot and demonstration scale facilities, and are looking for further opportunities.
- Based on DECC's emission projections for IPCC reporting purposes, it can be assumed that the $CO_2$ resource in Scotland will remain relatively stable (or even grow) over the next 20 years.
- Data for larger scale $CO_2$ emitters is readily accessible through the Scottish Pollution Release Inventory database, but there are at present only limited publicly available data for the current market demand for $CO_2$ in Scotland or the UK as a whole
- Scottish demand for $CO_2$ is estimated at **200,000 tonnes per annum** (a tenth of the estimated **2 million tonnes per annum** UK-wide), although this is subject to significant uncertainty.

- Current $CO_2$ demands in the UK are varied and include: Food & Beverage, Chemicals, Pharmaceuticals & Petroleum Industry, Metals Industry, Manufacturing & Construction, Rubber and Plastics Industry, Health Care, and the Nuclear Sector.
- Innovation in technology and market changes that lead to the development of new cost effective carbon based products may in time result in a closer match between emissions and the demand from $CO_2$ utilisation.
- Appreciating more about the subjective factors likely to shape perceptions of risk relating to new industrial technologies, like $CO_2$ utilisation, is important to their successful promotion; as is the selection of trusted communicators to convey information about proposed projects and plans.

**The overall recommendation of this report is that Scottish Enterprise should prioritise the development of a roadmap for $CO_2$ utilisation in Scotland to help accelerate its development and deployment.**

**In order to build a better evidence base, this report recommends a number of additional, more detailed projects. The information developed from these will enable Scottish Enterprise to take a more evidenced based approach to the formation of a $CO_2$ Utilisation Roadmap.**



Hyperlinks to sections in this document:

5.6 - Section 5.6 Inorganic Fertiliser

5.7 - Section 5.7 Mineralisation of $CO_2$

5.3 - Section 5.3 $CO_2$ derived fuels

5.5 - Section 5.5 Specialist chemicals

5.4 - Section 5.4 Chemical feedstocks

## Specialist Chemicals

Early stage research in CO$_2$ derived specialist chemicals is primarily focused on the development of highly efficient catalysts giving faster reaction rates, reduced energy requirements and high product selectivity. Products include linear carbonates, cyclic carbonates and polymers. One major advantage of CO$_2$ utilisation as a feedstock is its comparative safety when compared to current reagents such as phosgene. Using CO$_2$ as a renewable feedstock in the production of polymers is an advancing technology. Polyols derived from CO$_2$ are being used in the production of polyurethane foams for use in furniture and mattresses. Adhesives, resins and fillers derived from CO$_2$ are also reaching the construction materials market.

## CO$_2$ Derived Fuels

The transport sector is dependent on liquid hydrocarbon fuels to drive combustion engines. New clean technology is enabling electrical vehicles (full and hybrid), natural gas vehicles, fuel cell vehicles, and liquid fuels from non-fossil sources. There are advances in liquid fuels manufacture from biofuels and from gas-to-liquids which transform methane into syngas and then into a range of liquid fuels. Ideally the syngas would be made CO$_2$ rather than methane as the carbon source and hydrogen made from renewable energy powered electrolysis of water rather than the steam reformation of methane.

## Mineralisation of CO$_2$

Mimicking natural processes normally completed over geological timescales, the carbonation of minerals is based on the accelerated reaction of CO$_2$ with metal oxide bearing minerals such as silicates of calcium and magnesium to form inert carbonates that serves to lock carbon out of the atmosphere over the long-term in a stable, leakage free manner. CO$_2$ mineralisation can be completed with industrial CO$_2$ process emissions or CO$_2$ in combustion flue streams with little pre-treatment, as the mineralisation step itself is the capture process.

## Chemical Feedstocks

The feedstocks for the extensive manufacturing industry centred at Grangemouth predominantly derive from fossil fuels. A number of chemicals and their feedstocks can be derived from CO$_2$, i.e. methanol, urea, dimethylether, olefins etc. Supercritical and liquid CO$_2$ is classified as a green solvent and has a role to play in the bulk chemical industry replacing many more hazardous and environmentally damaging solvents, although ultimately the CO$_2$ will still be released to the atmosphere upon use. However, CO$_2$ can act as a switch which enables the solvent to change its properties allowing smaller volumes of solvent to be used and greater efficiency in process design.

## Inorganic Fertiliser

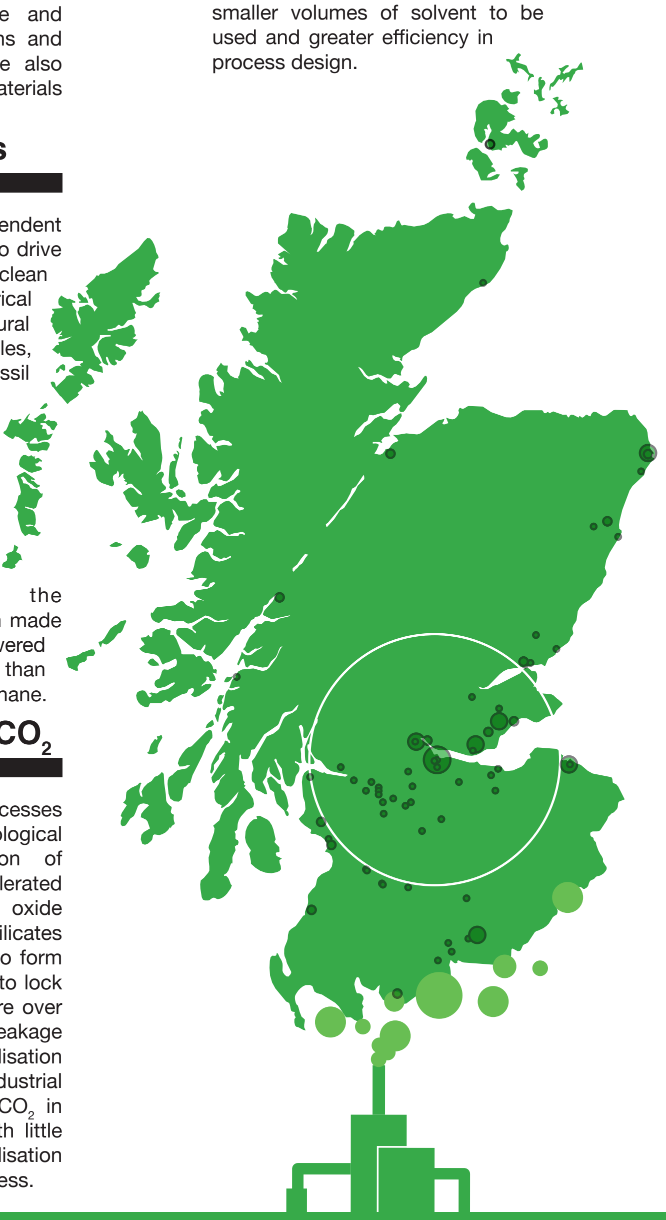
Scotland currently imports all of its inorganic fertiliser demand. CO$_2$ can be utilised to produce a pelletised carbonate type fertiliser that can be spread on fields with existing farm machinery. Biogenic CO$_2$ derived fertilisers align with Scotland's ambition to be a world leader in Green farming by providing a circular use of biogenic carbon coupled with low carbon energy inputs that could also potentially increase the soil organic matter too.

## Carbon Capture & Storage (CCS)

CCS involves the capture of CO$_2$ from a power station or industrial emissions source, transportation to a storage site and injection into deep underground porous geological formations. The North Sea basin is host to several world class offshore locations for the storage of CO$_2$. The main conceptual difference CCS and CCU is that the utilisation sector see CO$_2$ as a resource for re-use, whereas the storage sector regards CO$_2$ as an emission to be sequestered. The main practical difference is one of scale. To provide its primary goal of protecting the atmosphere, worldwide CCS needs to scale up to billions of tonnes of CO$_2$ per annum to help address the scale of carbon emissions. Over the near term CCU will be limited in its scale, as time is needed to develop products and market size.

## CO$_2$ EOR

Rather than simply capturing and storing CO$_2$ with little additional economic benefit beyond the CO$_2$ capture and transport supply chain, Scotland could use the captured industrial and power sector CO$_2$ emissions to provide a working fluid to enhance oil and gas recovery via CO$_2$-EOR. The technique would be used to extend the economic life of the North Sea basin by allowing a greater amount of hydrocarbons to be extracted.



**Key**

- • 10,000 tonnes
- ● 500,000 tonnes
- ● 1,000,000 tonnes
- ○ 50 miles from Grangemouth

# Introduction

To provide a sustainable future, the world's economies will have to decouple their economic activity from the historical level of damaging environmental impacts. Utilising $CO_2$ as a source of carbon for chemical feedstocks, fertilisers, fuels and building materials could eventually be a major part of this shift, as future economic activity will continue to need carbon for the creation of many products. Economic activity will increasingly need to consider a more detailed appreciation of carbon and $CO_2$ as it flows through the economy *e.g.* where this carbon comes from, and whether it can be used more than once before entering the atmosphere or being stored underground.

At a strategic level, carbon management has historically focussed on the reduction of carbon entering the atmosphere by fuel switching to lower-carbon alternatives, by increasing the efficiency of the process that uses the carbon, or by capturing the carbon before it enters the atmosphere and storing it underground. The first two have proved effective in several sectors such as the power sector, but the deployment of CCS technology at scale and its associated infrastructure has stalled on several occasions in the UK. This report introduces a complementary area for the strategic management of carbon through the re-use of carbon. However, depending on the definition of processes that come under $CO_2$ utilisation, **the demand for $CO_2$ relative to the overall supply (emissions) is extremely limited at this time, and therefore $CO_2$ utilisation SHOULD NOT be considered as an alternative to CCS when looking to mitigate $CO_2$ emissions.**

Many of the products that can be produced by using $CO_2$ as a carbon feedstock *e.g.* fuels, are themselves likely to emit $CO_2$ at their end-of-life stage, so the carbon can be thought of as being delayed in entering the atmosphere rather than being stopped altogether. If the re-use of $CO_2$ provides a greater economic activity from a single fossil carbon atom, then this would suggest a decoupling of economic activity from emissions to some degree. There is also a growing consensus that the carbon locked up in the mineral carbonation of various waste streams can be an effective long-term store of carbon, *e.g.* the use of carbonated material in lightweight building blocks in the construction sector is felt to remain in the built environment well after the initial building has been demolished. This is driven by the policies to encourage the reuse of construction waste in general.

CCS and the re-use of carbon through $CO_2$ utilisation should **both** be part of Scotland's overall strategy for $CO_2$ management. The two avenues have different drivers for their growth and different needs to accelerate their deployment, and are considered to be **complementary** rather than being competitive. Both share the potential to be significant growth areas in the future, but this will be governed by market developments driven by policy, as well as technological advances and sufficient levels of Government investment in infrastructure.

The UK Government's and the Scottish Government's own independent advisors (The Committee on Climate Change) believes that the cost of decarbonising future energy demands and industry in Great Britain will be cheaper with CCS (2050 timeframe). It is therefore believed that the decision to develop the necessary infrastructure for CCS in the UK is not a question of **if**, but of **when**; and when this happens it could be of benefit to the $CO_2$ utilisation sector too. It could also be of great interest for $CO_2$ Enhanced Oil Recovery (EOR). However, the scale of $CO_2$

utilisation demands is unlikely to be at the scale required to help the business case for the large infrastructure investments that CCS requires, whereas the demands from EOR could. This mismatch in $CO_2$ demand between CCS and $CO_2$ utilisation implies caution is required when considering how CCS and $CO_2$ utilisation may benefit each other's business case. $CO_2$ utilisation requires much smaller volumes of $CO_2$ compared to CCS at this time, due to the size of its potential markets that are limited, mainly because of cost disadvantages.

One of the typical reasons for this cost disadvantage in comparison to products that use fossil fuels, is that many $CO_2$ utilisation products require a significant energy input, which itself must come from low carbon sources. Many $CO_2$ utilisation processes would therefore benefit from access to low-cost electricity (at certain times), which may be an increasingly likely situation in Scotland due to the forecast increases in wind generation. The challenge however, is that the timing of this low-cost electricity will be variable, and there will be competition for this low-cost electricity from other demands too *e.g.* heat and transport.

Over the long-term, Scotland's significant renewable energy resource points to the potential of low-cost electricity (at certain times), and a question arises whether Scotland should continue to export as much of this to other geographical areas for additional value to be added elsewhere, or to try to encourage additional value to be created within Scotland itself. The production of hydrogen through electrolysis, which is an important feedstock for many $CO_2$ utilisation products, offers a technical route to create value for some of the electricity generated in Scotland. Electrolysis at a significant scale would also provide the additional advantages of security of supply for a hydrogen feedstock for all sectors, and the benefit of a highly dispatchable demand, which are both advantageous in a future world with much larger levels of weather dependent renewable generation. However, currently the most economic manner to produce hydrogen is through the steam reforming of methane, which if coupled to CCS infrastructure would also provide hydrogen with a low carbon footprint.

The stripping of carbon from fossil methane to produce hydrogen could provide the manufacturing complex at Grangemouth with part of a long-term vision to become a low carbon industrial hub. The carbon dioxide produced from the steam reformation of methane would be captured and stored using CCS infrastructure at an industrial scale. It could be host to one of Europe's low carbon refineries that produces synthetic liquid fuels, which are still likely be required in the long-term by certain parts of the transport sector. The aviation sector in particular has few options other than hydrocarbons, due to the necessary energy density trade-offs required for flight, and the challenge for this sector is potentially less to do with switching to a new fuel, but in changing how the existing fuel is manufactured. Having a significant electrolyser resource at Grangemouth may also be advantageous to a low carbon industrial cluster and the wider balancing of the electrical grid in Scotland too. With access to low carbon hydrogen through electrolysis or through methane stripped of its carbon (which is re-injected underground), additional industrial sources of carbon could be captured and utilised to produce synthetic aviation fuel.

If the Grangemouth region is to move towards becoming a low carbon manufacturing hub, the market for low carbon synthetic fuels of non-biological origin require to be developed at sufficient scale to allow investments to take place. The private sector will drive this forward at scale, but only when existing markets have been adapted to allow this to happen with a significant and profitable market pull.

Policy makers therefore have a role to play to increase the market for $CO_2$ derived products, which would be preferable at a European level rather than a Scottish or UK level in order to provide a market of sufficient scale. Given a greater potential market to compete within, technology providers and developers can move along their learning curves and reduce the unit costs of the technologies resulting directly from the scaling up of deployment.

# 1 What is $CO_2$ utilisation?

$CO_2$ utilisation is a term that covers the utilisation of the carbon dioxide molecule. It is often termed Carbon Capture and Utilisation (CCU), Carbon Dioxide Utilisation (CDU), or other similar variations. This report will use the terms $CO_2$ utilisation and CCU throughout, as both are commonly used interchangeably. In addition to the differing terms for $CO_2$ utilisation the scope of what is included as $CO_2$ utilisation is subject to variation too. The European Smart $CO_2$ transformation (SCOT) project[8] drew a boundary around the utilisation of $CO_2$ to involve a transformative step of the $CO_2$ molecule *e.g.* requiring the breaking of a carbon-oxygen bond. This means that using $CO_2$ as a solvent for extracting caffeine, using $CO_2$ in fire extinguishers, or carbonated drinks, $CO_2$-EOR *etc.* were considered to be **direct uses** of $CO_2$ rather than '$CO_2$ utilisation' by the SCOT project. On the other hand, the Zero Emissions Platform[9] views direct uses of $CO_2$ such as $CO_2$-EOR as being within the definition of CCU processes. Until there is wider agreement on the processes covered by $CO_2$ utilisation, it is easier for each report to continue to detail what it believes to be in scope in terms of that report.

## 1.1 $CO_2$ utilisation scope for this report

This report views the **direct uses** of $CO_2$ including $CO_2$-EOR to be **within** the scope of $CO_2$ utilisation, but separates out $CO_2$-EOR in discussion. Given that $CO_2$-EOR has recently been covered in detail elsewhere[10] this report focusses on the non-$CO_2$-EOR forms of $CO_2$ utilisation, and their potential in a Scottish context to take $CO_2$ and make products.

This report does not focus on the technical aspects of technologies for $CO_2$ utilisation in great detail, as readers are directed to several reports that provide greater depth.

These are:

- Carbon Counts, Ecofys report Implications of the Reuse of Captured $CO_2$ for European Climate Action Policies, 2013 [11]
- Power-to-Gas – A technical review, SGC Rapport 2013:284, 2013[12]
- Centre for Low Carbon Futures, Carbon Capture and Utilization in the Green Economy, 2011[13]
- Aresta *et al.,* The changing paradigm in $CO_2$ utilization, 2013 [14]

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[8] www.scotproject.org (online) accessed April 2016

[9] www.zeroemissionsplatform.eu/ (online) accessed April 2016

[10] http://www.sccs.org.uk/images/expertise/reports/co2-eor-jip/SCCS-CO2-EOR-JIP-Report-SUMMARY.pdf (online) accessed April 2016

[11] http://www.scotproject.org/sites/default/files/Carbon%20Count,%20Ecofys%20(2013)%20Implications%20of%20the%20reuse%20of%20captured%20CO2%20-%20report.pdf (online) accessed April 2016

[12] http://www.sgc.se/ckfinder/userfiles/files/SGC284_eng.pdf (online) accessed April 2016

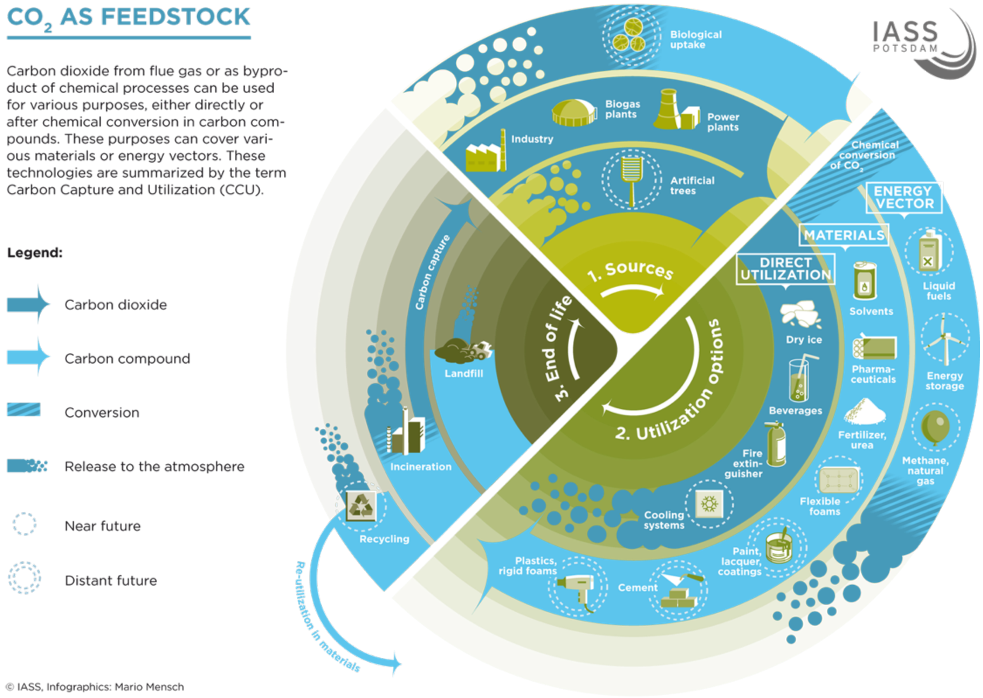
[13] http://co2chem.co.uk/wp-content/uploads/2012/06/CCU%20in%20the%20green%20economy%20report.pdf (online) accessed April 2016

[14] Aresta, M., Dibenedetto, A., Angelini, A.The changing paradigm in CO2 utilization, (2013) Journal of CO2 Utilization, 3-4, pp. 65-73.

## 1.2 Uses of carbon

Carbon is found in a broad range of different products. For example, in hydrocarbon fuels, in chemical building blocks such as ethane, in limestone for the production of Portland cement, in coke as a feedstock for the steel making process. In the case of fossil fuels or limestone for cement production, the carbon that has been locked away from the atmosphere over geological timeframes is extracted and brought back above ground. The carbon released from the use of these products will likely end up back in the atmosphere as the greenhouse gas $CO_2$. The increasing knowledge of the amount of $CO_2$ in the atmosphere caused by anthropogenic emissions, and the link between climate change and the amounts of atmospheric $CO_2$ is the main driver for the strategic management of carbon and carbon dioxide. The challenge to decouple economic activity from the emissions of $CO_2$ is one of the defining challenges for humanity this century.

Nature takes $CO_2$ and transforms it into carbohydrates via photosynthesis, and $CO_2$ is also able to be transformed synthetically into a wide range of products from chemical feedstocks to final products, to synthetic fuels, to inorganic fertiliser, to building materials (Figure 1). $CO_2$ can be used as a $C_1$ carbon source that replaces the carbon typically sourced from fossil fuels. The transformation of $CO_2$ into products requires other inputs too, which are typically energy inputs such as heat or electricity or material inputs such as hydrogen. It is imperative that these other inputs are low carbon themselves, in order to prevent a **net** overall increase in $CO_2$ emissions via a $CO_2$ utilisation process.



Carbon dioxide from flue gas or as byproduct of chemical processes can be used for various purposes, either directly or after chemical conversion in carbon compounds. These purposes can cover various materials or energy vectors. These technologies are summarized by the term Carbon Capture and Utilization (CCU).

© IASS, Infographics: Mario Mensch

*Figure 1 - $CO_2$ as a feedstock. With permission from Institute for Advanced Sustainability Studies e.V.*

The hydrocarbons of petroleum, natural gas and coal provide exceptional stores of hydrogen and carbon that release heat upon their combustion, with the by-products being water and $CO_2$. Hydrocarbons with higher hydrogen to carbon ratios such as methane ($CH_4$) provide more energy per unit of $CO_2$ released, as the ratio of energy released from hydrogen combustion to carbon combustion is greater. Other than their main uses as sources of primary energy, these hydrocarbons are also used as feedstocks to provide chemical supply chains with a ready source of hydrogen and carbon to be able to be recombined with other elements into a broad range of chemical intermediates and final products.

Rather than using the carbon from fossil hydrocarbons as the initial source of carbon, many chemical building blocks or feedstocks can use $CO_2$ as a **raw material** instead. Chemical intermediates produced with $CO_2$ are able to enter the chemical supply chain alongside their fossil derived equivalents to undergo further processing into further chemical intermediates or final chemical products. Synthesis gas (syngas) is a chemical industry feedstock that is a mixture of various ratios of carbon monoxide (CO) and hydrogen ($H_2$), which is of great industrial relevance in the production of other intermediate or final products such as methanol[15]. Syngas is a highly versatile gas; longer chain hydrocarbons can be created from syngas through Fischer-Tropsch reactions, which is especially relevant to the production of synthetic liquid fuels for hard to decarbonise parts of the transport system such as aviation.

A typical industrial scale method of syngas production uses the steam reformation of natural gas (or indeed coal gasification) and a water-gas shift reaction to produce the desired ratios of carbon monoxide and hydrogen. The former reaction requires significant amounts of energy (strongly endothermic), whereas the latter reaction is mildly exothermic and produces heat. Due to the significant energy requirements of the typical syngas production route, there would be an associated release of $CO_2$ to the atmosphere if the input energy was not from a low carbon energy source. Although using biomass and waste material as a source of the carbon and hydrogen for syngas does happen, the main sources of the carbon and hydrogen and the energy required to break the molecules apart are currently likely to be fossil based. This means that the products created from fossil syngas are ultimately fossil based too, which is therefore likely to ultimately lead to an increase in atmospheric $CO_2$ upon their eventual combustion as a fuel, or at the end-of-life incineration of a product. The technology to break apart hydrocarbons and put them back together to form different products is the core of the petrochemical sector, and Shell's Pearl[16] Gas to Liquids project in Qatar shows the scale that can be built to transform natural gas into liquid fuels.

Syngas provides a useful introduction to $CO_2$ utilisation, as it is characteristic of the process needs that typify many CCU processes. The production of syngas can be thought of as a provision of certain atoms and molecules in a required ratio, coupled with the energy required to break larger molecules apart.

Hydrogen is an important feedstock for many $CO_2$ utilisation processes, and the carbon footprint of its production is a crucial determinant of the carbon emissions associated with an overall CCU process or product.

Many CCU processes can substitute the need to use newly extracted (virgin) fossil carbon atoms with carbon atoms that have already been used (at least once), *e.g.* in an industrial or power sector setting. The re-use of carbon atoms means that the potential use of additional virgin

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[15] Methanol itself can be used as a fuel and also as a key $C_1$ building block for further processing in the chemical sector.

[16] http://www.shell.com/about-us/major-projects/pearl-gtl.html (online) accessed April 2016

underground carbon atoms might be avoided. This in essence is the difference between the linear paradigm of harvesting underground carbon, to use once, and then release $CO_2$ to the atmosphere and the circular paradigm of utilising carbon more than once before it enters the atmosphere, or is stored underground.

Hydrogen as an input to many CCU processes may be from decarbonised fossil supplies *e.g.* hydrogen from the steam reformation of methane that has had the $CO_2$ captured and stored, or renewable hydrogen from the electrolysis of water using low carbon electricity. Given a combination of the scaling of deployment of electrolysers and a reduction in the electricity price at times of potential electrical oversupply, the gap between fossil derived hydrogen (with the $CO_2$ captured and stored) and renewable hydrogen is likely to close over the long-term. As Scotland continues to decarbonise its primary energy supplies, it has access to low carbon sources of energy to produce hydrogen.

### Life Cycle Analysis

The need to undertake and publish transparent and rigorous life cycle analyses (LCA) for a CCU process needs to become an accepted common practice to determine its **net** $CO_2$ footprint. The aim of any CCU process should be to reduce the **net** amount of $CO_2$ being emitted to the atmosphere, as many products will still release $CO_2$ upon use (fuels) or at the end of their life (plastics). The important point is that this should be less than the equivalent amount that would be released via a conventional process, and thus there is an overall **net** reduction in comparison to a business as usual case. The concept of still having a **net** release of carbon dioxide, but it being less than would otherwise be the case with a comparable route is the defining argument for using CCS as an atmosphere protector *i.e.* less $CO_2$ is emitted than would otherwise be the case for the provision of electricity, heat or certain industrial materials from fossil fuels without CCS. It is also the defining argument for $CO_2$-EOR, where there is still a **net** release of carbon to the atmosphere, but less than the net release of carbon from oil that is not produced with $CO_2$-EOR. Again, differing oil and gas reservoirs will have different results from their life cycle analyses and the assumptions made about the amount of $CO_2$ to be sequestered[17].

When an LCA is undertaken, then similar boundary conditions **must** be used to allow comparison between different routes, processes and products. This means preliminary analyses carried out by Cradle to Gate (ISO14040) needs to be done up to the point where the product is produced. Full analysis by Cradle to Grave (ISO14044) must be applied when the final use of the product is also considered. Undertaking both methods for $CO_2$ utilisation, or preferably just Cradle to Grave in all cases, will bring additional clarity to the sector, and help build the evidence base that will ultimately be useful for policy makers too.

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[17] http://www.sccs.org.uk/images/expertise/misc/SCCS-CO2-EOR-JIP-Carbon-Balance.pdf (online) accessed April 16

# 2 What are the major differences between $CO_2$ utilisation and CCS?

There may be mutual benefits to the CCU sector from the development of the CCS sector, and vice versa, but it is helpful to understand that there are some major differences between the two sectors too.

The main conceptual difference between them is that the $CO_2$ utilisation sector regards $CO_2$ as a resource for re-use, whereas the CCS sector regards $CO_2$ as an emission to be sequestered in geological storage for the long-term. **The main practical difference is one of scale**, as until markets for $CO_2$ utilisation products appear at volume, its potential demand for $CO_2$ is likely to be limited in comparison to the potential demand from CCS.

CCS is a carbon mitigation activity that protects the atmosphere by sequestering carbon underground in long-term geological stores. Due to its necessary scale, it can be viewed as a national infrastructure development project in the UK, which will require significant levels of public sector support to develop. The announcement in November 2015 by the UK Government regarding the cancellation of the CCS commercialisation fund and withdrawal of the capital grant has been seen by the CCS and CCU communities as a retrograde step that has had a damaging impact on the level of trust within the nascent supply chain for CCS. The knowledge that the North Sea basin is host to several world class offshore locations for the storage of $CO_2$, and the fact that several industrial areas also have the potential to be connected to these suggests the long-term logic of Government policy and public sector funding revisiting this area.

The size and characterisation of these geological formations and proximity to significant areas of industrial activity put the UK and Scotland in particular in a favourable international position, as the world moves to more long-term storage or reuse of fossil $CO_2$ as part of an overall strategy for carbon management.

This major difference between CCS and $CO_2$ utilisation lies in the focus of the two sectors. The $CO_2$ utilisation sector is primarily focussed on reusing $CO_2$ as a resource, and **NOT** as an exercise in carbon mitigation. A $CO_2$ utilisation process will provide a **net** carbon benefit, but the size of this can only be verified with a life cycle analysis, which needs to be transparent about its boundary conditions and consideration of any avoided emissions. In comparison, the primary focus for CCS is protecting the atmosphere by carbon mitigation. Many of the products that can be produced by using $CO_2$ as a carbon feedstock *e.g.* fuels, are themselves likely to emit $CO_2$ at their end-of-life stage, so the carbon can be thought of as being delayed in entering the atmosphere rather than being stopped altogether. If the re-use of $CO_2$ provides a greater economic activity from a single fossil carbon atom, then this would suggest a decoupling of economic activity from emissions to some degree. There is also a growing consensus that the carbon locked up in the mineral carbonation of various waste streams can be an effective long-term store of carbon, *e.g.* the use of carbonated material in lightweight building blocks in the construction sector is felt to remain in the built environment well after the initial building has been demolished. This is driven by the policies to encourage the reuse of construction waste in general.

With a CCS system - $CO_2$ is captured from large point sources, prevented from entering the atmosphere, transported and stored underground in geological formations which are chosen for their ability to retain the $CO_2$ in a timeline which is measured in thousands of years.

This difference in focus has a major impact on the scale of infrastructure required for the two areas. To provide its primary goal of protecting the atmosphere, CCS needs to scale to millions of tonnes of $CO_2$ per year to help address the scale of carbon emissions and to justify the cost of the infrastructure – the more $CO_2$ sequestered the better, both from an environmental and a unit cost of infrastructure investment point of view. Over the near term however, $CO_2$ utilisation is likely to be limited in its scale, as it will take time to develop and increase the markets for $CO_2$ utilisation products.

Where possible economies should take advantage of **BOTH** $CO_2$ utilisation and CCS to decouple emissions from economic activity, but in many places one may be favoured over another due to regional and local factors. Scotland is in a highly fortunate position in that it can consider both, and with the right investment, encouragement and market frameworks over the long-term, both may grow to be significant areas of economic activity.

| | Scale | Main aim |
|---|---|---|
| **$CO_2$ utilisation** | A range of volumes required dependent on the type of activity. Smaller modular volumes, <10,000 tonnes per annum could be utilised by mineralisation and the production of fertiliser. If a greater market for synthetic fuels develops, then the volumes for $CO_2$ required would correspondingly increase. | To utilise $CO_2$ as a carbon resource for the creation of products. |
| **Carbon Capture and Storage** | Large volumes required to justify the infrastructure investment.<br>Millions of Tonnes per annum in a Scottish context. | To protect the atmosphere by sequestering $CO_2$ over the long-term in a geological store. |
| **$CO_2$-Enhanced Oil Recovery** | Large volumes required to justify the infrastructure investment. | $CO_2$-EOR's main aim is to generate additional fossil fuels by utilising $CO_2$ as a working fluid rather than a source of carbon. |

*Table 1 – Major differences between $CO_2$ utilisation and Carbon Capture and Storage and $CO_2$-EOR*

# 3 What is the size of Scotland's $CO_2$ resource?

## 3.1 Scottish Pollution Release Inventory Database

The best source of data for existing Scottish $CO_2$ emissions are from the Scottish Environmental Protection Agency's (SEPA) Scottish Pollution Release Inventory Database[18]. The most recent full set of available data is used for this report (from 2014). The Scottish Pollution Release Inventory Database can be searched by Map, Company, Pollutant, Waste, Industry Sector, Local Authority and Postcode. It is a requirement for operators who have $CO_2$ emissions in excess of **10,000 tonnes per annum** to report data to the Scottish Pollution Release Inventory. For emitters **<10,000 tonnes per annum** reporting is voluntary and thus SEPA have incomplete data. All emitters are required to report emissions to air from combustion but not all emitters have reported emissions relating to process, *i.e.* SEPA confirmed that for the distillery sector in particular, all of the distillery sector have reported carbon dioxide emissions to air from hydrocarbon combustion but only some have reported emissions relating to the venting to atmosphere of the biogenic source of $CO_2$ from the fermentation process. SEPA confirmed that the operators of Scottish Pollution Release Inventory sites submit data following SEPA's online guidance and in some cases this reporting also follows other reporting schemes, such as the EU Emission Trading Scheme (EU-ETS).

With regards to reporting of $CO_{2,}$ the operator is required to use the best available information to hand. However, operators are not required to install or consider additional monitoring processes to provide their Scottish Pollution Release Inventory return. They have to report the total emission of the substance leaving the site at a pollutant level (*i.e.* from all processes on the site associated with the activity giving rise to the particular pollutant) in the calendar year. Figure 2 and Figure 3 show a map of Scotland of the point source $CO_2$ emitters in 2014 with totals greater than 10,000 tonnes, mapped by postcode.

Grangemouth is clearly the location for any strategic aspiration to create a $CO_2$ utilisation market of scale in Scotland, as it would be a major hub of potential CCS infrastructure having access to significant volumes of $CO_2$ coupled with a deep and broad knowledge base within the supply chains for the Chemical Sciences sector. Grangemouth is also Scotland's largest manufacturing region.

The distance of 50 road miles centred on the manufacturing complex at Grangemouth was chosen as an arbitrary distance for analysis from a possible location for a CCS infrastructure cluster. This value was based on the transport of low-value bulk industrial gases such as oxygen, nitrogen and carbon dioxide, where economic transportation distances are thought to be about 200 kilometres from the production plant. It was estimated that within Scotland, for lower value carbon dioxide with higher capture costs, that the limit for tanker distance would be less than half of this. So, 50 miles was chosen for this analysis.

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[18] http://www.sepa.org.uk/environment/environmental-data/spri/ Contains SEPA data © Scottish Environment Protection Agency and database right 2016. All rights reserved. (online) accessed April 2016

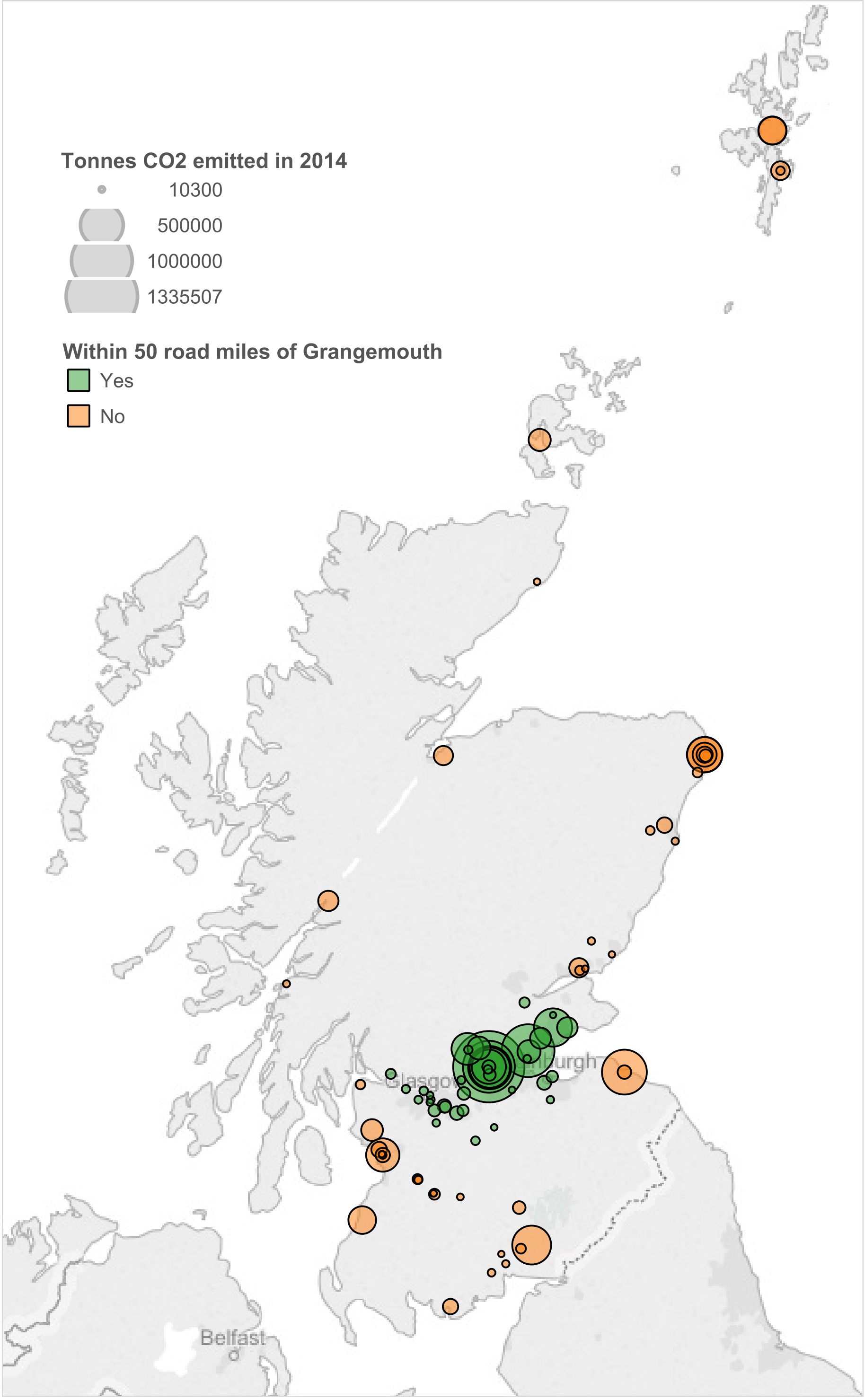

*Figure 2 – Locations of SEPA Scottish Pollution Release Inventory Database reporting companies for $CO_2$ emissions above 10,000 Tonnes in 2014 (Longannet is not shown). Green colour indicates point source is within 50 road miles of Grangemouth, orange colour indicates the point source is greater than 50 road miles away from Grangemouth.*

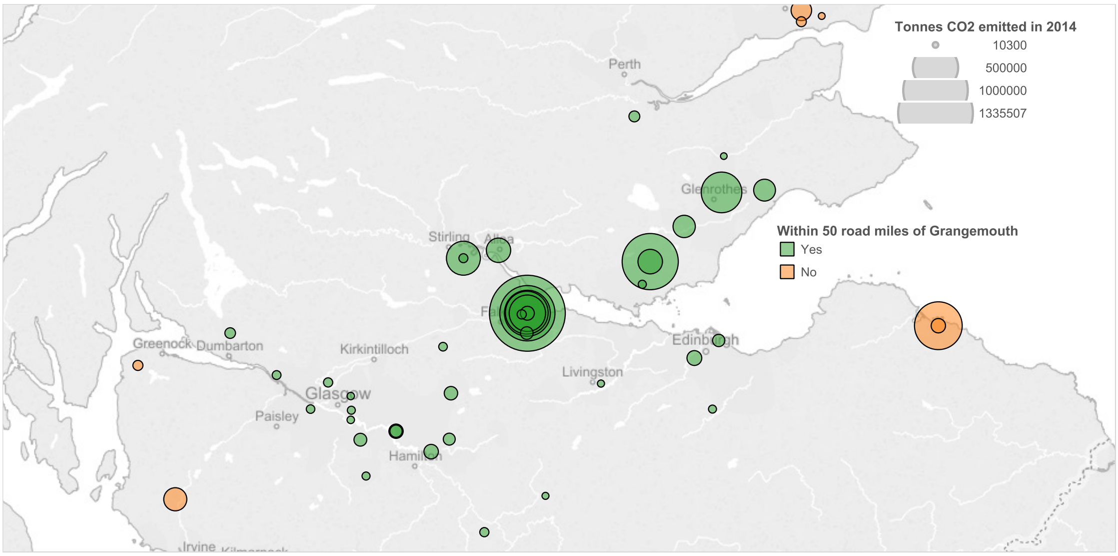

*Figure 3 – Locations of SEPA Scottish Pollution Release Inventory Database reporting companies for $CO_2$ emissions above 10,000 Tonnes in 2014 (Longannet is not shown). Green colour indicates point source is within 50 road miles of Grangemouth, orange colour indicates the point source is greater than 50 road miles away from Grangemouth.*

There are 88 emitters that registered greater than **10,000 tonnes per annum** (**tpa**) of $CO_2$ emissions for 2014, which all together totalled **19.2 million tpa**. However, just one emitter, Longannet coal fired power station, represented 52% of these emissions at **9.2 million tpa**. Given the closure of Longannet in late March 2016, its associated emissions have been excluded from further analysis. The remaining 87 emitters, totalling **10 million tpa** of $CO_2$, have been split across 10 categories and are shown in Figure 4. Building on previous studies[19] [20], a simple estimate of the potential volume of $CO_2$ that can be captured for storage or utilisation was made for each site with a value of either 33%, 66% or 90%, resulting in an estimated total capture potential from large emitters across Scotland of **7 million tpa**.

The Scottish Pollution Release Inventory database does not hold specific details of the purity or type of $CO_2$ emissions and is something that currently needs to be raised directly with the operator of the site.

Over the last 10 years, extensive background activity has been completed on both industrial and power sector CCS projects across the UK. With multiple sources of $CO_2$, clear entry specifications are required to ensure the long-term integrity of a $CO_2$ transportation network and its $CO_2$ storage facilities. National Grid Carbon have devised a standard specification and $CO_2$

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[19] Ineos, 2013. 'An Industry Perspective: Significant Challenges and Potential Costs of CCS' http://www.sccs.org.uk/images/events/2013/ICCS-workshops/Workshop2/JacquelineLobban.pdf (online) accessed April 2016

[20] SCCS, 2014. 'Opportunities for Industrial CCS in Scotland' http://www.all-energy.co.uk/__novadocuments/54249?v=635376478385170000 (online) accessed April 2016

specification used for the Teesside Collective Industrial CCS Project Feasibility Study[21] assumed that the high-quality specification for captured $CO_2$ associated with industrial and power emissions means that all these sources are available for $CO_2$ utilisation.

| | | | | |
|---|---|---|---|---|
| $CO_2 > 95.5\%$ purity | $H_2O < 50$ ppm | $O_2 < 10$ ppm | Pressure 100 barg | Temperature 35 °C |

*Table 2 – Example $CO_2$ specification for CCS pipeline transport*

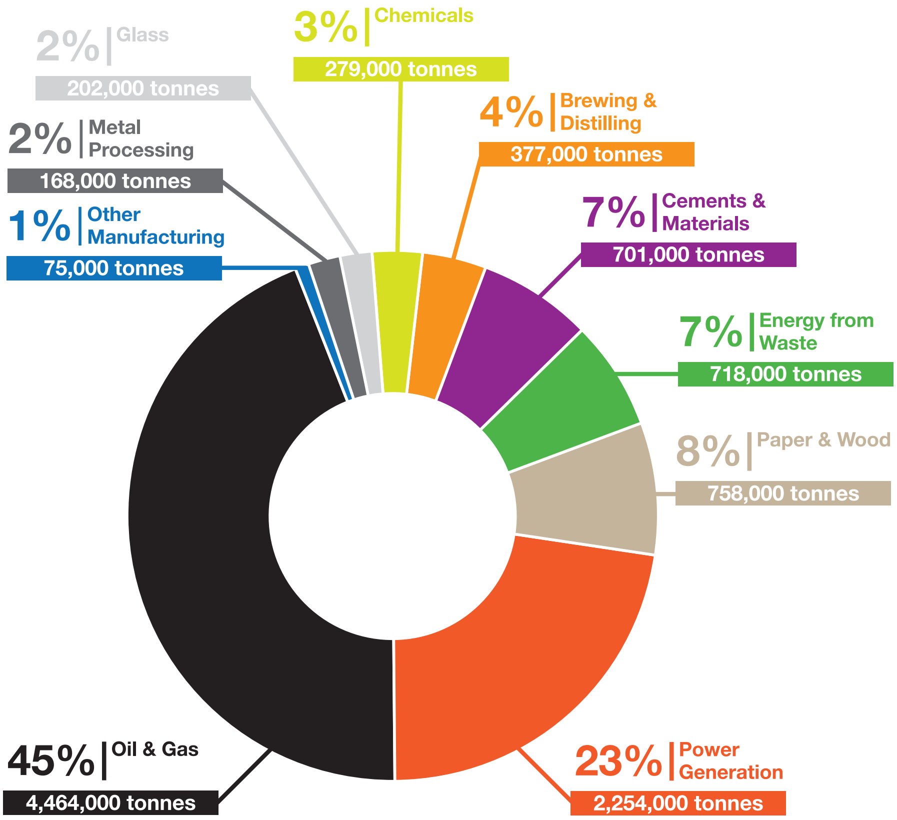

*Figure 4 – Analysis of $CO_2$ Emissions Data from the SEPA Scottish Pollution Release Inventory Database*

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[21] Teesside Collective, 2015. 'Teesside Collective reports: Blueprint for Industrial CCS in the UK' http://www.teessidecollective.co.uk/teesside-collective-blueprint-for-industrial-ccs-in-the-uk/ (online) accessed April 2016

## 3.2 $CO_2$ emissions within 50 road miles of Grangemouth

Forty locations are at or within 50 road miles of Grangemouth[22], representing **5.9 million tonnes per annum** (**tpa**) of emissions with an estimated capture potential of **3.6 million tpa**. However, the 12 largest sites emit over **100,000 tpa** each, which in total represents **5.15 million tpa** of emissions with an estimated capture potential of **3.1 million tpa**, and are shown in Figure 5.

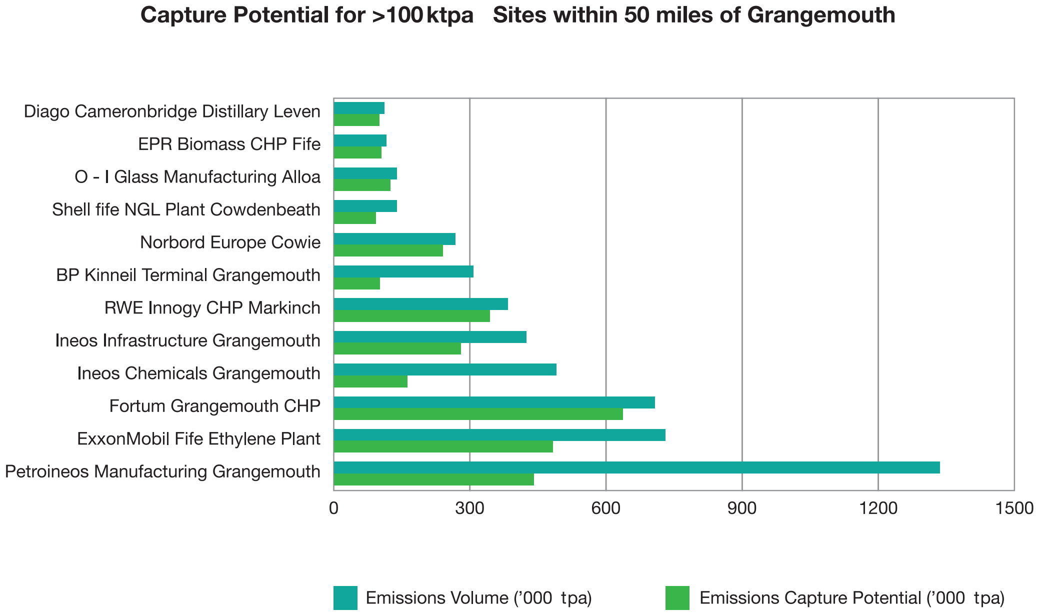

*Figure 5 – Carbon capture potential for the 12 largest emission sites within 50 miles of Grangemouth with a simple estimated capture value of either 33%, 66% or 90%.*

## 3.3 $CO_2$ from biomass and other organic matter

For 10 out of the 87 locations, just over **1.3 million tpa** originates from a biomass source, as detailed in the Scottish Pollution Release Inventory, which could present a potential for Bio-Energy Carbon Capture & Storage / Utilisation (BECCS/BECCU). However, only three of these locations are within 50 road miles of Grangemouth; Cameronbridge Distillery in Leven, Norbord in Cowie, and the RWE Innogy CHP plant in Markinch, with an estimated total of approximately **0.5 million tpa** able to be captured and from a biomass origin. **CCS with these locations could potentially result in a carbon negative outcome.** The other seven locations provide a further **0.7 million tpa** of capture potential from biomass, which could be available for CCU, but is not likely to be connected to CCS infrastructure due to their locations. Technically a number of the energy from waste plants can state some if not all their feedstock is biomass, *i.e.* the EPR Biomass CHP uses poultry litter, but these are currently shown as 0% biomass in the Scottish Pollution Release Inventory, so additional data would help to firm up estimates.

Anaerobic digestion (AD) also provides a source of $CO_2$ as a by-product from the processing of organic matter such as food waste, pig or cattle slurry, energy crops, municipal solid waste from

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[22] Road mile distance was cross checked with road mileage software between postcodes.

households and organic solid waste from industry. As the number of anaerobic digesters in Scotland increases, so too does the biogenic $CO_2$ resource from organic matter. If an AD plant injects biogas into a natural gas grid, then most of the $CO_2$ requires to be removed for the biogas to meet the specifications for injection, which suggests an opportunity for $CO_2$ utilisation. However, if the biogas is to be combusted onsite, it is may be unlikely that the $CO_2$ would be removed from the biogas prior to combustion.

## 3.4 The Scotch Whisky Distillery sector

The Scotch Whisky distillery sector should be highly attractive for $CO_2$ utilisation. The $CO_2$ released from the fermentation process is simple to capture from the fermentation vessel vents, and therefore low cost to capture, and is a high purity biogenic source. There are 115 distilleries across Scotland including the three largest Girvan, Cameronbridge and North British grain distilleries, which are large enough to fall within the reporting threshold of the Scottish Pollution Release Inventory database for their reportable emissions. The four smaller Invergordon, Strathclyde, Glen Turner and Loch Lomond grain distilleries and all 108 malt distilleries fall below the reporting threshold for reportable emissions. The sector in total is estimated to present an estimated **500,000 tpa** of biogenic $CO_2$ capture potential from the fermentation process. However, these will range in scale from **1000** to **40,000 tonnes per annum** per site, *e.g.* a **10 million litres** of alcohol per annum malt distillery is estimated to produce *circa* **7,400 tpa** of capture ready biogenic fermentation $CO_2$. SEPA have recommended engaging the Scotch Whisky Association to validate fermentation carbon emissions from its members and Scottish Pollution Release Inventory sites. The two clusters of distilleries in Speyside and Islay may offer opportunities for a $CO_2$ utilisation cluster of greater scale, by connecting multiple distilleries to local $CO_2$ infrastructure and a single $CO_2$ utilisation innovation park.

The $CO_2$ resource from the Scottish Brewing sector is small in comparison. The Tennent Caledonian brewery in Glasgow, with a major share of the Scottish market could be viewed as a $CO_2$ utilisation opportunity at an estimated 8400 **tonnes per annum** of biogenic $CO_2$, but other brewing companies should be engaged to understand their $CO_2$ resources and level of interest *e.g.* BrewDog.

## 3.5 Size of the $CO_2$ resource in Scotland

For this report, Scotland's resource of $CO_2$ for $CO_2$ utilisation is estimated as the capture potential of the top 12 largest emitters less than 50 road miles from Grangemouth which equals **3.1 million tonnes per annum** of which **0.5 million** is from biomass. The seven bioenergy locations greater than 50 road miles away from Grangemouth is estimated to be **0.7 million tpa** and the distilling sector fermentation emissions have been estimated to be **0.5 million tpa.** The volumes of $CO_2$ available from smaller point sources in island, rural and agricultural communities and smaller industrial point sources are unknown.

| | **Potential $CO_2$ resource in tonnes per annum** |
|---|---|
| **The top 12 largest emitters within 50 road miles of Grangemouth** | **3.1 million (0.5 million is biomass)** |
| **Seven large bioenergy locations greater than 50 road miles away from Grangemouth** | **0.7 million** |
| **Biogenic fermentation $CO_2$ from distillery sector** | **0.5 million** |
| **Smaller point sources in island, rural and agricultural communities** | **?** |
| **Smaller industrial point sources** | **?** |
| **Total** | **4.3 million** |

*Table 3 – Scotland's potential $CO_2$ resource in tonnes per annum*

The total of these gives a value of **4.3 million tonnes per annum for the size of the $CO_2$ resource in Scotland**, of which **1.7 million tonnes per annum** is estimated to be biogenic, which is a significant resource.

## 3.6 Future $CO_2$ supplies

Although a new unabated coal fired power station is unlikely to ever pass the planning regime in Scotland for a number of environmental reasons, a feasibility study is currently being completed for the Caledonia Clean Energy Project, which is a **570 MWe** coal fired power station that would capture 90% of its $CO_2$ emissions and be connected to future CCS infrastructure at a site near Grangemouth. This integrated gasification and combined cycle technology uses coal as its feedstock. If the project were to proceed, a further **3.8 million tonnes per annum** could be made available after completion. This would increase the supply of a $CO_2$ resource in Scotland in excess of **8 million tpa** after completion.

For reference Figure 6 is a version of DECC's emissions projections for IPCC reporting purposes[23] that has been slimmed down to show emissions associated within specific energy, power and industrial sectors. For 2014, the relevant UK wide $CO_2$ emissions amount to **251 million tpa** and are projected to fall to **139 million** and **108 million tpa** by 2025 and 2035 respectively. Whilst these falls are significant, nearly every sector associated with the Scottish SPRI emissions data

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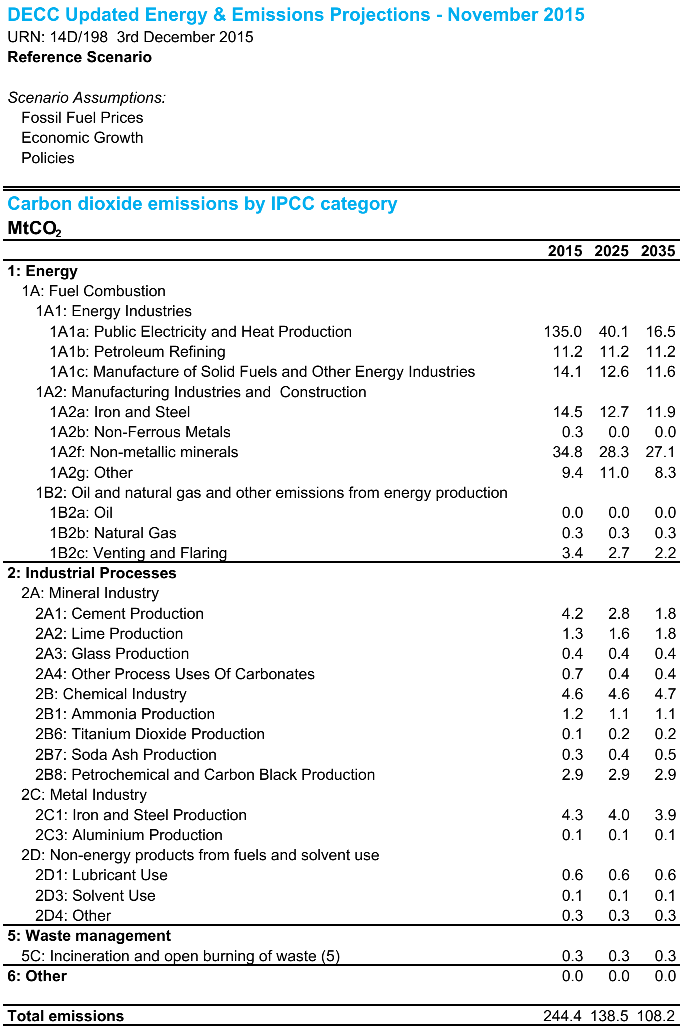
[23] DECC, 2015. 'Updated Energy and Emissions Projections 2015 Annex C: Carbon Dioxide Emissions by IPCC category' https://www.gov.uk/government/publications/updated-energy-and-emissions-projections-2015 (online) accessed April 2016

detailed in Figure 6 remains flat or actually increases, *i.e.* petroleum refining. Thus, subject to the business viability of the emitters, **it could be assumed that the potential supply of $CO_2$ from within Scotland for $CO_2$ utilisation remains stable (or even grows) over the next 20 years.**

This analysis has not included **direct air capture** of $CO_2$, which can be considered to be a l**imitless resource** only constrained by the energy inputs and capital costs of the direct air capture units. There may be some areas where this would be locally of interest, but this analysis has concentrated on the existing and potential point sources of $CO_2$ that have a higher concentration than the atmosphere, and are likely to be the initial resources that deployment of $CO_2$ utilisation would exploit.



**DECC Updated Energy & Emissions Projections - November 2015**
URN: 14D/198 3rd December 2015
**Reference Scenario**

*Scenario Assumptions:*
Fossil Fuel Prices
Economic Growth
Policies

**Carbon dioxide emissions by IPCC category**
**$MtCO_2$**

| | 2015 | 2025 | 2035 |
|---|---|---|---|
| **1: Energy** | | | |
| 1A: Fuel Combustion | | | |
| 1A1: Energy Industries | | | |
| 1A1a: Public Electricity and Heat Production | 135.0 | 40.1 | 16.5 |
| 1A1b: Petroleum Refining | 11.2 | 11.2 | 11.2 |
| 1A1c: Manufacture of Solid Fuels and Other Energy Industries | 14.1 | 12.6 | 11.6 |
| 1A2: Manufacturing Industries and Construction | | | |
| 1A2a: Iron and Steel | 14.5 | 12.7 | 11.9 |
| 1A2b: Non-Ferrous Metals | 0.3 | 0.0 | 0.0 |
| 1A2f: Non-metallic minerals | 34.8 | 28.3 | 27.1 |
| 1A2g: Other | 9.4 | 11.0 | 8.3 |
| 1B2: Oil and natural gas and other emissions from energy production | | | |
| 1B2a: Oil | 0.0 | 0.0 | 0.0 |
| 1B2b: Natural Gas | 0.3 | 0.3 | 0.3 |
| 1B2c: Venting and Flaring | 3.4 | 2.7 | 2.2 |
| **2: Industrial Processes** | | | |
| 2A: Mineral Industry | | | |
| 2A1: Cement Production | 4.2 | 2.8 | 1.8 |
| 2A2: Lime Production | 1.3 | 1.6 | 1.8 |
| 2A3: Glass Production | 0.4 | 0.4 | 0.4 |
| 2A4: Other Process Uses Of Carbonates | 0.7 | 0.4 | 0.4 |
| 2B: Chemical Industry | 4.6 | 4.6 | 4.7 |
| 2B1: Ammonia Production | 1.2 | 1.1 | 1.1 |
| 2B6: Titanium Dioxide Production | 0.1 | 0.2 | 0.2 |
| 2B7: Soda Ash Production | 0.3 | 0.4 | 0.5 |
| 2B8: Petrochemical and Carbon Black Production | 2.9 | 2.9 | 2.9 |
| 2C: Metal Industry | | | |
| 2C1: Iron and Steel Production | 4.3 | 4.0 | 3.9 |
| 2C3: Aluminium Production | 0.1 | 0.1 | 0.1 |
| 2D: Non-energy products from fuels and solvent use | | | |
| 2D1: Lubricant Use | 0.6 | 0.6 | 0.6 |
| 2D3: Solvent Use | 0.1 | 0.1 | 0.1 |
| 2D4: Other | 0.3 | 0.3 | 0.3 |
| **5: Waste management** | | | |
| 5C: Incineration and open burning of waste (5) | 0.3 | 0.3 | 0.3 |
| **6: Other** | 0.0 | 0.0 | 0.0 |
| **Total emissions** | 244.4 | 138.5 | 108.2 |

*Figure 6 – Consolidated view of DECC's UK Energy & Emissions Projections*[24]

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[24] adapted from https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/483926/Annex-c-carbon-dioxide-emissions-by-IPCC-category-updated_03-DEC-2015.xls (online) accessed April 2016

# 4 What is the size of existing $CO_2$ demand in Scotland?

Whilst data for larger scale $CO_2$ emitters is readily accessible through the Scottish Pollution Release Inventory database, there are currently very little publicly available data for the current market demand for $CO_2$ in Scotland or the UK as a whole. In order to place an order of magnitude estimate on the scale of Scottish $CO_2$ demand, data from a research report for Industrial Gas Manufacturing[25] was used. This indicates that the UK $CO_2$ market has a current annual turnover of £210m, with annual growth over the next 5 years projected at 1.8%. Equating this turnover value to a tonnage using an average rate of **£105 per tonne,** gives an order of magnitude estimate of **2 million tonnes per annum** for the UK. The three businesses, BOC, Air Products and Air Liquide make up 78% of the Industrial Gas Manufacturing market share in the UK, with a further nine businesses making up the remainder. Taking Scotland's share of this at an estimated 10% would give a Scottish demand of **200,000 tonnes per annum**. However, the £210 million per annum UK turnover is thought to include the $CO_2$ utilised in the production of urea on Teesside. As Scotland does not produce urea, and as the production of urea is a major demand for $CO_2$ this **200,000 tonnes per annum** value for Scotland is subject to even greater uncertainty than the tonnage for the UK as a whole.

$CO_2$ is usually extracted as a co-product from other industrial gas manufacture at ammonia fertiliser plants and from the food and drink sector after alcohol fermentation. Other industrial sources of $CO_2$ are from thermal cracking of hydrocarbons and hydrogen production via fossil fuel gasification rather than steam reformation.

Many companies in the Industrial Gas Manufacturing sector see hydrogen as a key growth priority. For example, in 2011, BOC constructed Britain's first commercial-scale, open-access hydrogen refuelling station at Honda's Swindon manufacturing facilities and have since gone on to install the largest facility in the UK with Aberdeen City Council's Kittybrewster hydrogen refuelling station. Similarly, Air Products have a number of hydrogen installations across London, and ITM Power have installed a number of hydrogen refuelling stations too. Going forward the use of hydrogen as an alternative fuel for heat and transport is projected to become more common. Hydrogen can be generated on a modular basis by electrolysers from electricity, which itself needs to be low carbon electricity to produce hydrogen with a low carbon footprint. This $CO_2$ could be technically useful for utilisation, but the difference in volumes between supply and demand and the potentially short lived nature of certain CCU products mean that a proper life cycle analysis is required to determine the **net** $CO_2$ benefits.

**Large scale hydrogen production is currently via the steam reforming of natural gas resulting in the release of capture ready carbon dioxide. If hydrogen is to become a major player in decarbonising heat and transport energy requirements and this is from fossil hydrogen, its growth will require an equivalent growth in CCS to mitigate its carbon footprint, to put the fossil carbon back underground.**

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[25] IBIS World 'Industrial Gas Manufacturing in the UK May 2015'

## 4.1 How is $CO_2$ currently utilised in Scotland?

The current market size of the UK is broadly estimated at **2 million tonnes per annum** (with a large margin for error). Non-pipeline $CO_2$ is supplied in solid, liquid or gaseous form in bulk or cylinder format. Most $CO_2$ is distributed at very low temperature and high pressure requiring heavy specialised insulated containers which incurs significant transport costs. Thus, where possible, industry participants locate close to their customers. Ideally large scale industrial gas generation and subsequent use/conversion is located on the same or adjacent site(s) and connected through pipelines *e.g.* the use of the $CO_2$ from an ammonia plant that is utilised by a co-located urea plant.

$CO_2$ has a wide variety of applications in the UK such as:

- **Food & Beverage:** Quick freezing, surface freezing, chilling and refrigeration in the transport of foods. Cold sterilisation. Carbonation of soft drinks, beers and wine. Solvent for many organic compounds such as de-caffeinating coffee. Product dispensing propellant and extraction agent, *e.g.* air displacement during canning. Flavour/Fragrance production using supercritical $CO_2$ as a solvent. Yields of plant products grown in greenhouses can increase by 20% by enriching the air inside the greenhouse with carbon dioxide.
- **Chemicals, Pharmaceuticals & Petroleum Industry:** Raw material in the chemical process industry, *e.g.* production of methanol and urea. Enhanced Oil Recovery.
- **Metals Industry:** In the manufacture of casting moulds to improve metal hardness. Deburring and grinding.
- **Manufacturing & Construction:** Shield gas in MIG/MAG welding. Welding efficiency. Sandblasting alternative with solid $CO_2$ pellets (Dry Ice).
- **Rubber and Plastics Industry:** Flash removal
- **Multi-Industry:** Refrigeration and cooling, particularly of food. Pipe freezing. Inert gas in chemical processes. Fire extinguisher/suppression systems. Dry fabric cleaning. Supercritical extraction.
- **Health Care:** Respiration stimulant.
- **Environmental:** Aerosol propellant. Effluent treatment, *i.e.* pH correction to neutralise alkaline water.
- **Sports:** Aerosol propellant for injury treatments. Small $CO_2$ canisters used as propellant for paintball and airguns, and as an inflation cartridge for bicycle tyres.
- **Specialised:** Algae grown for food, biofuel *etc.* Graphene. Special effects.

The source of and cost of $CO_2$ used to carbonate drinks produced by AGBarr, Highland Spring Water, Coca Cola, *etc.* is currently unknown and could be qualified in a further phase of work that looks into the current $CO_2$ demands in Scotland in greater detail. A rough calculation is presented in Appendix 3 which gives AGBarr's use of $CO_2$ in Scotland at around **600 tonnes in 2012**. From this rough calculation, it would seem that the carbonated drinks demand could easily be technically supplied from the Scottish Distilling Sector. Indeed, North British Distillery in Edinburgh capture $CO_2$, compress it and sell it the soft drinks industry.

Up until *circa* 2001 fermented $CO_2$ was captured for reuse at Diageo's Cameronbridge grain distillery until the plant was no longer cost effective and thus removed. However, in the USA, Aemetis are currently adding a liquefied carbon dioxide capture facility to their ethanol biorefinery in Keyes, California. It is expected to cost $15 million with estimated annual power and maintenance costs at $3million. The plant is equivalent in size to Cameronbridge capturing an estimated **100,000 tonnes** of $CO_2$ with an estimated revenue expected to be around $14 million annually ($142/tonne as a mix of wholesale and retail) demonstrating that an attractive return on investment for capturing $CO_2$ is achievable in certain cases. To further emphasise this point, a Scottish SME in the oil and gas sector is currently importing solid $CO_2$ at a cost of £125/tonne. In the USA, Pioneer Energy[26], a NASA Technology Spinoff, have developed a $CO_2$ Craft Brewery Recovery System that recovers fermentation $CO_2$ for carbonation use at the same facility with an indicative two-year payback in a typical market of $220-$330 per tonne.

In 2015, Pale Blue Dot completed the Business Case[27] for the Teesside Collective Industrial CCS project. This identified that just under 3 million tonnes of $CO_2$ per annum could be captured, transported and sequestered for a full supply chain cost of £95/tonne. The capture cost element amounted to £45/tonne which was for the volume weighted average of the undiscounted financial support for all four of the industrial processes covered by the feasibility study. The individual capture costs ranged from £37-215/tonne for the different process industries and the different scales at which they operate. The Teesside Collective project provides Scottish Enterprise an insightful cost benchmark for carbon capture potential at Grangemouth.

Whilst the applications for $CO_2$ are varied, **the potential near-term demand relative to Scotland's emissions is low, to the extent that $CO_2$ utilisation SHOULD NOT be considered as a substitute for CCS**. The two different sectors are aiming for different scales of deployment, and are considered **complementary**. A difference in storage timelines with regard to material impact on climate change exists between CCS and $CO_2$ Utilisation.

Innovation in technology and market development that leads to the development of new cost effective carbon based products may in time result in a closer match between emissions and the demand from $CO_2$ utilisation.

Figure 7 shows the scale of the estimated $CO_2$ demand and supplies in Scotland.

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[26] NASA, 2016. 'CO2 Recovery System Saves Brewers Money, Puts Bubbles into Beer' spinoff.nasa.gov/Spinoff2016/cg3.html (online) accessed April 2016

[27] PBDE, 2015. 'Industrial CCS on Teesside – The Business Case' http://www.pale-blu.com/perspectives/teesside-collective-industrial-ccs-business-case-launched (online) accessed April 2016

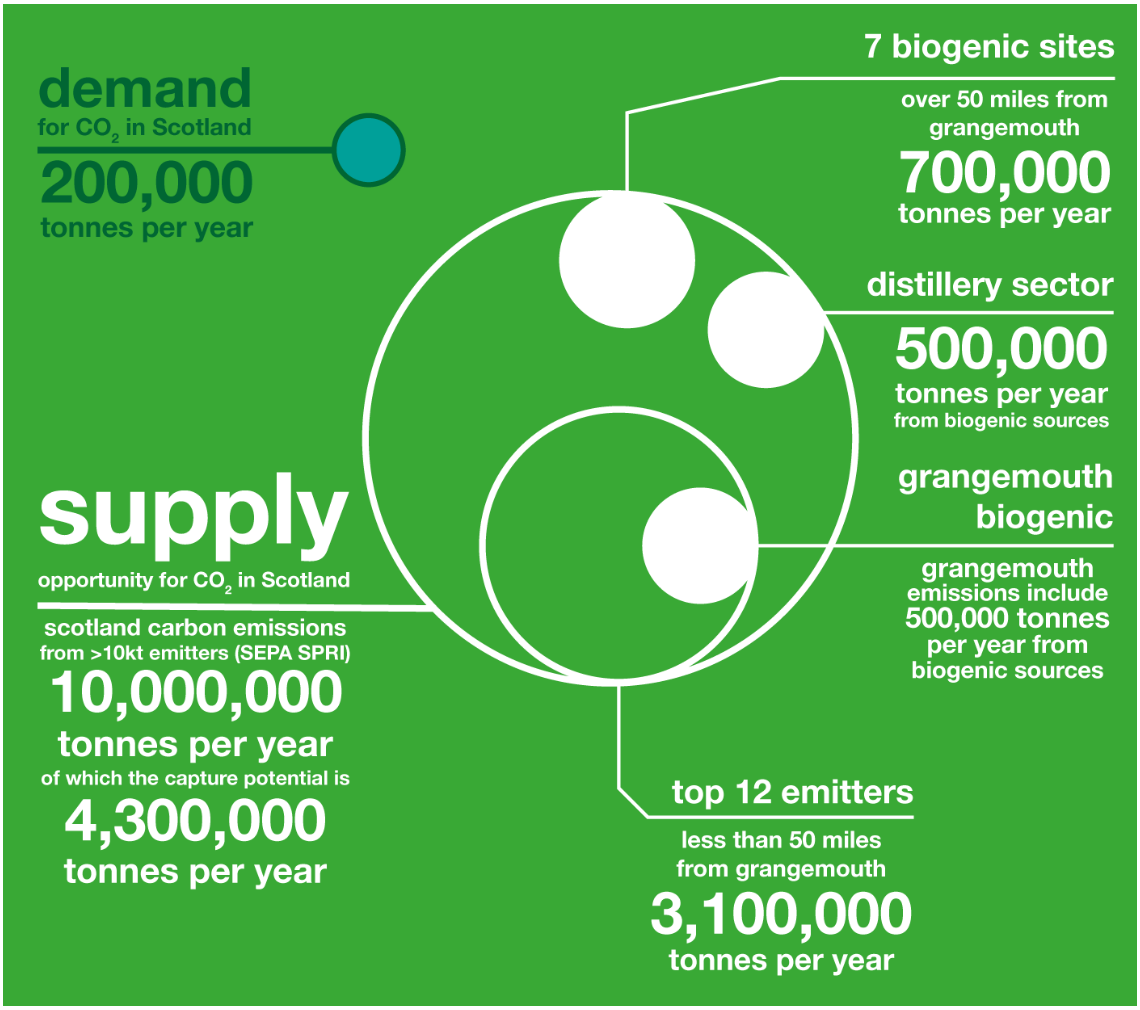


*Figure 7 – Graphic showing scale of $CO_2$ demand and resources in Scotland.*

# 5 What could Scotland do with its $CO_2$ resource?

There are a number of avenues that Scotland could seek to investigate in terms of its $CO_2$ resource, which are presented in Table 4. The different avenues are influenced by the location and the type of $CO_2$ resource *e.g.* the different volumes and locations of $CO_2$ resources lend themselves to different uses.

Larger point sources have the scale to lend themselves to CCS or to provide the significant volumes of $CO_2$ needed to benefit the oil and gas sector through enhanced oil recovery. However, these options would need to be connected to an as yet to be built CCS or $CO_2$-EOR infrastructure.

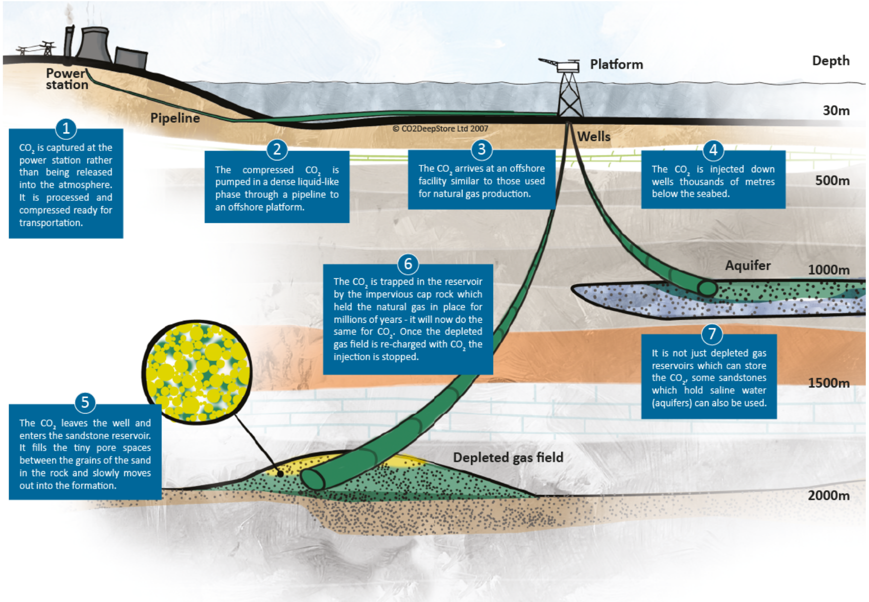
Smaller point sources that are unlikely ever to be connected to this infrastructure lend themselves to the production of fertilisers, mineralised wastes, and potentially to $CO_2$ derived fuels dependent on the location, access to additional material and energy inputs, and local or regional demands.

| Type of $CO_2$ resource | Tonnage of $CO_2$ per annum | Could connect to CCS $CO_2$-EOR infrastructure? | Suggested target use for $CO_2$ |
|---|---|---|---|
| **The top 12 largest emitters within 50 road miles of Grangemouth** | **3.1 million (0.5 million is biomass)** | **YES** | **CCS, $CO_2$-EOR, $CO_2$ derived fuels, chemical feedstocks, specialist chemicals** |
| **Seven bioenergy locations greater than 50 road miles away from Grangemouth** | **0.7 million** | **NO** | **$CO_2$ derived fuels, inorganic fertiliser** |
| **Biogenic fermentation $CO_2$ from distillery sector** | **0.5 million** | **NO** | **Inorganic fertiliser** |
| **Smaller point sources in island, rural and agricultural communities** | **?** | **NO** | **$CO_2$ derived fuels, inorganic fertiliser** |
| **Smaller industrial point sources** | **?** | **NO** | **Mineralised wastes** |
| **Total** | **4.3 million** | | |

*Table 4 – Scotland's $CO_2$ resources in tonnes per annum and suggested target uses*

## 5.1 Carbon capture and storage

Carbon capture and storage is a process involving the capture of carbon dioxide ($CO_2$) from a power station or industrial emissions source before it reaches the atmosphere, its transportation to a storage site and injection into a deep underground porous geological formation, where it is stored over the long-term. A visual overview is provided in Figure 8.



© CO2DeepStore Ltd 2007

① $CO_2$ is captured at the power station rather than being released into the atmosphere. It is processed and compressed ready for transportation.

② The compressed $CO_2$ is pumped in a dense liquid-like phase through a pipeline to an offshore platform.

③ The $CO_2$ arrives at an offshore facility similar to those used for natural gas production.

④ The $CO_2$ is injected down wells thousands of metres below the seabed.

⑤ The $CO_2$ leaves the well and enters the sandstone reservoir. It fills the tiny pore spaces between the grains of the sand in the rock and slowly moves out into the formation.

⑥ The $CO_2$ is trapped in the reservoir by the impervious cap rock which held the natural gas in place for millions of years - it will now do the same for $CO_2$. Once the depleted gas field is re-charged with $CO_2$ the injection is stopped.

⑦ It is not just depleted gas reservoirs which can store the $CO_2$, some sandstones which hold saline water (aquifers) can also be used.

*Figure 8 – Overview of the carbon capture and storage process*

There are three main ways the $CO_2$ can be captured; pre-combustion, post-combustion and oxyfuel.

- Pre-combustion capture involves the direct collection and compression of a $CO_2$ source or the gasification or reforming of a fuel (*e.g.* coal or gas respectively) into hydrogen/syngas and $CO_2$. The hydrogen/syngas can then be used for electricity generation, feedstock, heating or transport.
- Post-combustion capture uses a chemical process to absorb the $CO_2$ in waste exhaust gases following combustion of a fuel and can be retrofitted to existing power stations or industrial sources.
- Oxyfuel capture uses a feedstock of pure oxygen during combustion, resulting in a high purity $CO_2$ waste stream.

Further details on the background to CCS technology in a Scottish context can be found through the Scottish Carbon Capture and Storage website[28] and the recent report for the ETI[29] titled *'Progressing Development of the UK's Strategic Carbon Dioxide Storage Resource: A Summary of Results from the Strategic UK CO2 Storage Appraisal Project'.*

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[28] www.sccs.org.uk (online) accessed April 2016

[29] http://www.eti.co.uk/wp-content/uploads/2016/04/D16-10113ETIS-WP6-Report-Publishable-Summary.pdf (online) accessed May 2016

## 5.2 $CO_2$-Enhanced Oil Recovery

Rather than simply capturing and storing $CO_2$ with little additional economic benefit beyond the $CO_2$ capture and transport supply chain, Scotland could use the captured industrial and power sector $CO_2$ emissions to provide a working fluid to enhance oil and gas recovery via $CO_2$-EOR. The wider economic benefit of this avenue for $CO_2$ was investigated in a 2015 SCCS report on economic multipliers for $CO_2$-EOR[30]. Overall, the technique would be used to extend the economic life of the North Sea basin by allowing a greater amount of hydrocarbons to be extracted.

$CO_2$-EOR has been a common technique for several decades in North America but only in certain areas, as the source of $CO_2$ in nearly all cases is geological rather than from the industrial or power sectors. However, one example that does source $CO_2$ from the power sector is the Boundary Dam project[31] that captures up to 90%[32]of the $CO_2$ emissions from a 115MW coal fired power station, and sells this for enhancing oil recovery from a regional oil field. It is the first post-combustion coal-fired CCS project in the world.

It should be noted that $CO_2$-EOR can still have a net increase in overall emissions when downstream emissions from the transport refining and combustion of crude oil are included. The report from the Scottish CCS group[33] in 2014 details how to provide an analysis of the mitigation potential of a couple of case studies in the North Sea, and provides examples of the potential net overall increase and decrease when downstream emissions are included. The difference in cradle-to-gate and cradle-to-grave life cycle analysis is presented and is highly significant.

There is some debate in the $CO_2$ utilisation community whether $CO_2$-EOR should be classified as CCU process or a carbon capture and storage process. The view of this report is that it does not particularly matter as either description is valid. However, given the findings from a recent article from Mabon and Littlecott titled 'Stakeholder and public perceptions of $CO_2$-EOR in the context of CCS– Results from UK focus groups and implications for policy'[34] it would seem a sensible approach to have $CO_2$-EOR projects publish their forecast and actual life cycle analyses for a system boundary focused on the operations **AND** for a system boundary that includes downstream emissions from the transport refining and combustion of the crude oil too. In this manner, wider stakeholders can compare the financial benefit alongside the environmental benefits of $CO_2$-EOR.

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[30] https://www.era.lib.ed.ac.uk/bitstream/handle/1842/15723/SCCS-CO2-EOR-JIP-CO2-EOR-Multiplier-Study.pdf?sequence=1 (online) accessed April 2016

[31] http://saskpowerccs.com/ (online) accessed April 2016

[32] http://saskpowerccs.com/ccs-projects/boundary-dam-carbon-capture-project/ (online) accessed April 2016

[33] http://www.sccs.org.uk/images/expertise/misc/SCCS-CO2-EOR-JIP-Carbon-Balance.pdf (online) accessed April 2016

[34] Mabon, L., Littlecott, C., Stakeholder and public perceptions of CO2-EOR in the context of CCS – Results from UK focus groups and implications for policy, International Journal of Greenhouse Gas Control, Volume 49, June 2016, pp128-137, http://dx.doi.org/10.1016/j.ijggc.2016.02.031

## 5.3 $CO_2$ derived fuels – Power-to-fuels

**Liquid fuels**

The transport sector is overwhelmingly dependent on liquid hydrocarbon fuels due to the synergistic development of internal combustion engines for cars, trucks, ships and aircraft jet engines that are primarily reliant on the liquid form of fuels. The relative cost of liquid hydrocarbon fuels, and their highly-developed supply chains, provides end users with a highly convenient form of stored energy for transport, which is of clear benefit when the mobility provided by the fuel's energy also has to transport the fuels themselves. The costs of extraction and refining of crude oil to produce refined transport fuels is less than the manufacture of synthetic fuels from hydrogen and $CO_2$. The chemical energy has already been embedded in the crude oil by natural processes, whereas the chemical energy still requires to be embedded in synthetic fuels, which has an associated cost for the energy. The risks of liquid fuels are well known, and the supply chains are arguably one of the most established and wide reaching of any products in the world.

However, technological advances are starting to disrupt this historical dependency of transport energy demands on liquid fossil based fuels *e.g.* electrical vehicles (full and hybrid), natural gas vehicles, fuel cell vehicles, and liquid fuels from non-fossil sources. There have been advances in the manufacture of liquid fuels from biofuels, and from gas-to-liquids that uses natural gas as a feedstock to create syngas, which is then transformed into a range of liquid fuels. Shell's Pearl[35] Gas-to-Liquids project in Qatar creates liquid fuels that have a range of benefits over the conventional fuels produced from refining petroleum. The advantages of these fuels include the reduction in the number of aromatic rings in the fuel (which means less particulates), virtually no sulphur in the fuel due to the removal of sulphur from the natural gas feedstock, which means less oxides of sulphur ($SO_x$), and less nitrogen in the fuel, which means less oxides of nitrogen ($NO_x$). The fuel is marketed as having lower local emissions than petroleum based fuels, which is clearly of increasing interest to areas that have problems with their local air quality. Liquid fuels can be created from syngas where the carbon has come from $CO_2$ rather than methane, the hydrogen has come from the electrolysis of water rather than the steam reformation of methane, and the energy is from low carbon sources rather than a fossil source such as methane.

The benefits of $CO_2$ derived liquid fuels are similar to the benefits for the gas-to-liquids fuels stated in the previous paragraph, as they would be similar products, just using different sources for the feedstock and energy inputs.

However, the costs of producing liquid fuels from $CO_2$ and low carbon sources is unlikely to be competitive with natural gas-to-liquids or petroleum based refined fuels, as there is the additional cost for the energy that needs to be stored in the synthetic fuels itself. The cost of synthetic fuels is therefore highly dependent on the cost of the energy required to create them. Therefore, policies will have a crucial role to play here to help markets develop for different synthetic fuels, where they can compete with each other in a protected or target driven part of the overall market, rather than compete directly with fossil fuel derived fuels. A target for a % of synthetic fuels of non-biological origin to provide part of the fuel mix may be the type of policy

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[35] http://www.shell.com/about-us/major-projects/pearl-gtl.html (online) accessed 2016

target that would help, but whether this is something that should be attempted by Scotland itself (rather than UK legislation) is something that would need greater understanding. Of specific interest for Scotland, is the potential to harness a greater amount of the wind resource at a national and even a local level, and use this power to create syngas that can be transformed into liquid fuels to cover transport, chemical sector feedstocks and potentially even some heating demand. As Scotland decarbonises its electrical system well in advance of many other countries, the use of power-to-fuels could provide a whole energy systems benefit that is applicable to Scotland precisely because it is decarbonising its electrical system faster than other countries.

**As power-to-liquid technologies develop, these are likely to become economic sooner in areas that have abundant renewable resources, and more expensive liquid fuels**. Scotland has many of these areas in its island and rural communities, and so understanding their $CO_2$ resources in better detail would be a valid first step in exploring this avenue.

The scale of liquid fuel demand in the UK is marked as 'Transport Fuels' on the diagram in Figure 9; which is the sum of Diesel, Petrol and Aviation fuel in GWh per day and is calculated from monthly values from the Department of Energy and Climate Change[36]. This is broadly 1600 GWh per day for Great Britain, and taking a value of 10% of this for Scotland provides a conservative estimate of Scotland's transport fuel needs of 160GWh per day. Looking at aviation fuel alone (not shown on the graph) gives values of broadly 400 GWh per day for Great Britain and 40GWh per day for Scotland when estimated at 10% of the Great Britain value. Although the amount of liquid fossil fuels is expected to eventually drop considerably for personal vehicles and light duty commercial vans, **aviation in particular is still likely to require the energy density of liquid fuels well into the future**.

**When the CCS infrastructure is eventually developed in Scotland, the creation of low carbon aviation fuels at Grangemouth could be an opportunity for power-to-liquids at significant scale that could be complementary to a gas-to-liquids development at Grangemouth too**.

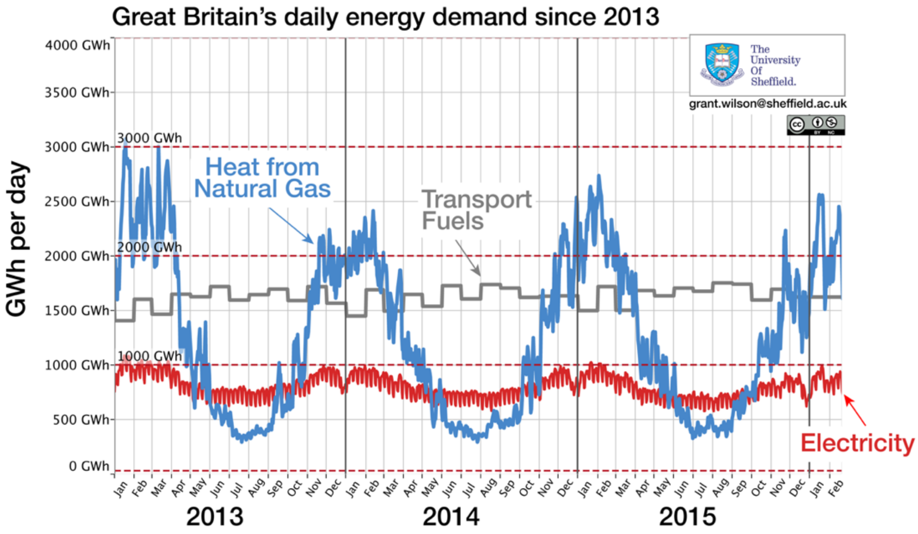

*Figure 9 – Diagram of Great Britain's energy vectors on a daily basis*

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[36] Deliveries of petroleum products for inland consumption – DECC table ET 3.13

## Methane

Power-to-methane is similar to power-to-liquids as they both use low carbon electricity to create hydrogen and combine it with $CO_2$ to transform it into a different energy form *i.e.* to create a gaseous or liquid fuel. The phrase 'power-to-gas' is often used to describe this area, and can be used to mean either power-to-hydrogen and also power-to-methane. This report will use power-to-methane to describe the combination of $CO_2$ with hydrogen to produce a gaseous hydrocarbon. The creation of syngas from the electrolysis of water and reduction of $CO_2$ to CO uses a methanation step such as a Sabatier reaction to create the methane. This can be a highly exothermic reaction with a major challenge being to control the heat build-up in the reactor.

The technology has been around for many decades and is well described in a recent paper by Götz *et al* [37], with the efficiency of creating hydrogen from electricity described as 70%, and the efficiency of the further methanation step being 78%, giving a total efficiency of 55% from electricity to methane. The combination of $CO_2$ with hydrogen to produce synthetic methane therefore introduces an additional step with extra equipment costs and energy losses over the electrolysis of hydrogen alone. The benefits of this additional step to create methane are to be found downstream from the process, where there is no limit to the blending concentration of synthetic methane in natural gas infrastructure, or the need to change end user equipment. The creation of synthetic methane provides a drop-in replacement for fossil derived natural gas without significant infrastructure changes.

Germany has progressed this concept and technology over the last few years with the Audi e-gas demonstrator project being an example[38]. The 6 MW of electrolysers at the plant have also provided network services to the electrical grid as they meet local grid code standards to be able to partake in that market. The project uses a supply of $CO_2$ from a co-located biogas plant and injects the methane directly into the natural gas grid. As shown in Figure 9, the natural gas demand in Great Britain for heating is not only of a significant overall scale, but also has the greatest seasonality of all the final use energy demands.

For industrial and biogas point sources of $CO_2$ that are near or connected to the natural gas infrastructure in Scotland, this may be an interesting opportunity to further explore.

## Methanol

Methanol is a key commodity chemical as well as being a fuel. It was originally produced from wood fermentation which gives rise to its common name 'wood alcohol'. However, due to high global demand it is now produced from petrochemical sources through the catalytic conversion of syngas (a combination of carbon monoxide and hydrogen). In order to make methanol production more sustainable, new approaches are needed which include the catalytic reduction of carbon dioxide with green hydrogen, obtained through electrochemical splitting of water using renewable energy. Demand for methanol is high due to its versatility. It is commonly used in organic synthesis as a solvent and a reagent. Typical products using methanol as a feedstock

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[37] Götz, M. et al., 2016. Renewable Power-to-Gas: A technological and economic review. Renewable Energy, 85, pp.1371–1390. www.sciencedirect.com/science/article/pii/S0960148115301610

[38] https://www.audi-mediacenter.com/en/press-releases/world-premiere-audi-opens-power-to-gas-facility-784 (online) accessed April 2016

include esters (flavours and fragrances), ethers (DME, MTBE) and polymers (methanol-formaldehyde resins, methyl acrylates, *etc.*). It is also a transport drop-in fuel that is permitted in varying concentrations around the world, including China where it can be used as a 20% additive to diesel. Under its use as a fuel (rather than a chemical feedstock) methanol derived from $CO_2$ is considered 'renewable' by the Fuel Quality Directive (depending on the source of energy involved in its production).

One of the most successful demonstrations of $CO_2$ utilisation technology has been the George Olah methanol production facility operated by Carbon Recycling International (CRI)[39] in Iceland. This operates using geothermal energy and co-produced geothermal carbon dioxide to produce **6,300 tonnes per annum** of methanol. The overall conversion is exothermic but requires energy to overcome the activation energy ($\Delta H$ (298 K, 50 bar) = -40.9 kJ/mol) of the process and to produce the required hydrogen through water electrolysis.

$3H_2O \rightarrow 3H_2 + 1.5O_2$ Electrolysis

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

$CO_2 + 3H_2O \rightarrow CH_3OH + 1.5O_2$ **Overall**

The reaction is catalysed by a number of earth abundant catalysts including copper and at high temperature and pressure (up to 250 °C and 100 bar). However, the process offers a number of opportunities for improvement by industrial integration of different waste heat and gas streams and as CRI and Mitsubishi in Japan have demonstrated, it is economically viable with the correct market frameworks.

Methanol may be an attractive $CO_2$ utilisation product for Scotland due to its versatility as a potential liquid renewable fuel and as an important chemical feedstock. Further dialogue should be progressed with industry to understand the opportunities for methanol in Scotland at a distributed level and also at a future larger scale at Grangemouth.

Figure 10 provides a graphical representation of the production of methane or methanol using $CO_2$ as a feedstock.

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[39] ttp://www.cri.is/ (online) accessed April 2016

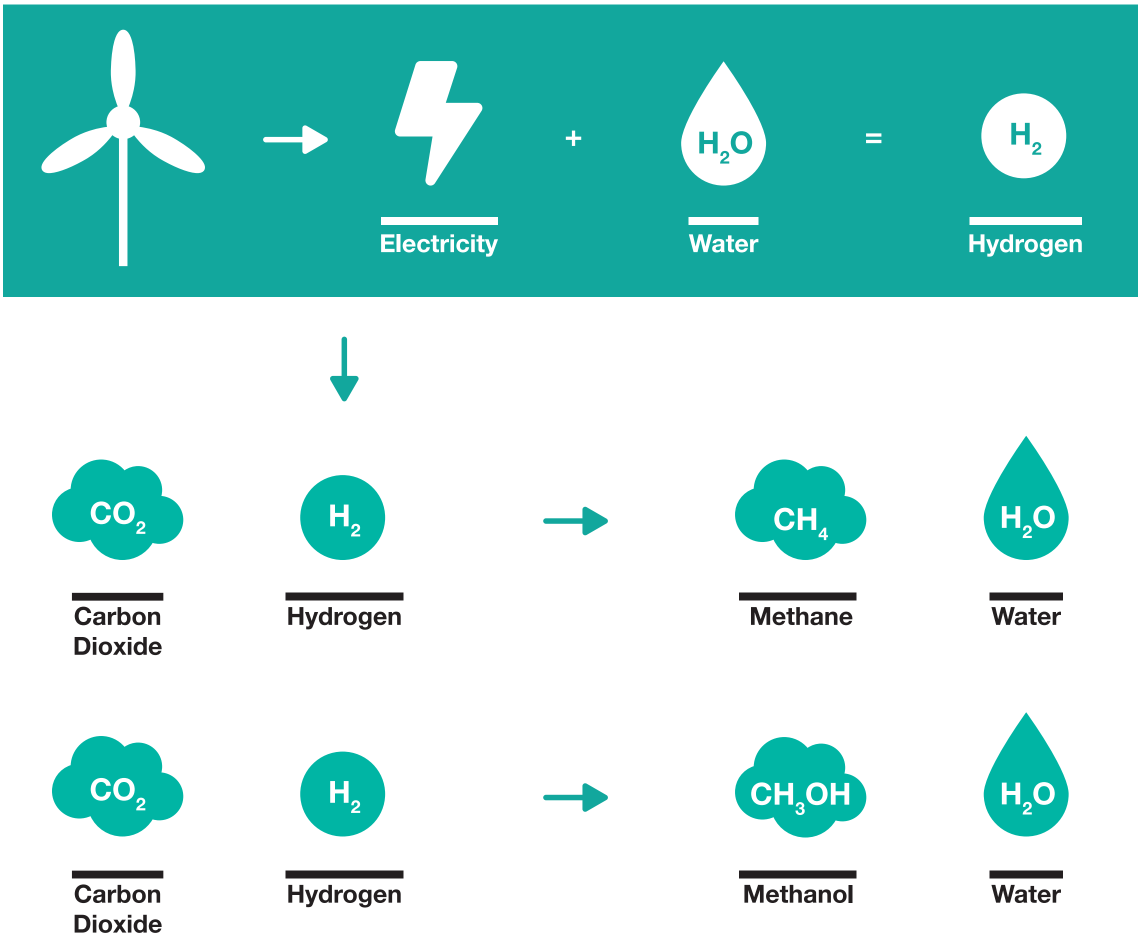

*Figure 10 – Graphic for production of $CO_2$ derived fuels.*

## 5.4 Chemical feedstocks

Scotland has a large chemical industry centred on the Grangemouth industrial complex. Moving the chemical industry towards more sustainable forms of feedstocks is a daunting challenge at the commodity end of the feedstock market, as there are clear cost benefits of using petroleum or natural gas compared to synthetic fuel based feedstocks.

The feedstock market for Grangemouth is also becoming more international and diversified in nature *e.g.* Ineos have made a significant investment in ethane infrastructure due to a combination of the reduction in natural gas production from the North Sea over the last ten years and the shale oil and gas boom in the US. The first shipment of shale gas ethane took place in the second half of 2016[40].

Methanol is a major intermediate for the chemicals industry (in addition to its potential as a fuel). By volume, methanol is one of the top five commodity chemicals with over 70 million tonnes per annum produced globally. It can be used as solvent, antifreeze, in waste water treatment and is a precursor to many other chemicals; being transformed into hydrocarbons, halides, carbonyls, carboxylic acids, amines and ethers.

Over 180 million tonnes of urea is produced annually by reacting $CO_2$ with ammonia. Whilst 90% of urea is used as a fertiliser it is also an important chemical precursor in pharmaceuticals, fine chemicals and polymer industries particularly for resins and adhesives. More sustainable methods of producing urea using renewable hydrogen to create green ammonia are advancing in technological readiness.

Dimethylether (DME) is both a clean alternative fuel and a commodity chemical utilised in the production of olefins. DME has a large market potential due to its similar properties to LPG. Using hybrid catalysts DME can be synthesised from $CO_2$ and $H_{2.}$

Olefins such as ethene and propene are key building blocks in the petrochemical industry. However, they are highly energy intensive to produce, and a considerable contributor to the $CO_2$ emissions produced by the chemicals industry. Olefins can be produced from $CO_2$ and hydrogen and Fischer-Tropsch synthesis or via methanol or DME. The economic viability for the $CO_2$ based process relies on access to cheaper renewable hydrogen to drive costs down, however the increase of shale gas production in the US is driving the costs of fossil-derived olefins down.

Although the $CO_2$ is not incorporated or transformed into a new product, supercritical and liquid $CO_2$ is used in the bulk chemical industry as a solvent. $CO_{2,}$ both in its liquid and supercritical states, is classified as a green solvent and can replace many more hazardous and environmentally damaging solvents, although it will still impact global warming due to the release of $CO_2$ to the atmosphere upon use. $CO_2$ is a highly versatile solvent and can act as a switch which enables the solvent to change its properties allowing smaller volumes of solvent to be used and greater efficiency in process design.

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[40] http://www.ineos.com/sites/grangemouth/moving-forward (online) accessed April 2016

**$CO_2$ utilisation offers a route for the Chemical Sciences sector to diversify its feedstock base**, and further details should be considered in a more detailed piece of analysis. The cost base of the industry is however highly price sensitive to feedstocks, and a legislative market change may be required to provide a market for more sustainable forms of non-fossil based feedstocks.

## 5.5 Specialist chemicals

Over 90% of organic chemicals are derived from fossil carbon which potentially could be replaced by carbon from $CO_2$; Figure 11 shows some of these potential routes. Many chemicals are currently being targeted for production from $CO_2$ and research ranges from TRL 1-9, however the majority of research is at the lower TRL levels and not expected to reach industrial application in the near-term. Research is primarily focused on the development of highly efficient catalysts giving faster reaction rates, reduced energy requirements and high product selectivity. Products at higher TRL levels include linear carbonates, cyclic carbonates and polymers. In selecting target products careful analysis of market potential versus production costs must be undertaken as it is perceived that some routes although technically possible will not be economically viable without market changes. One major advantage of the utilisation of $CO_2$ as a feedstock in chemical production is its comparative safety when compared to current reagents such as phosgene.

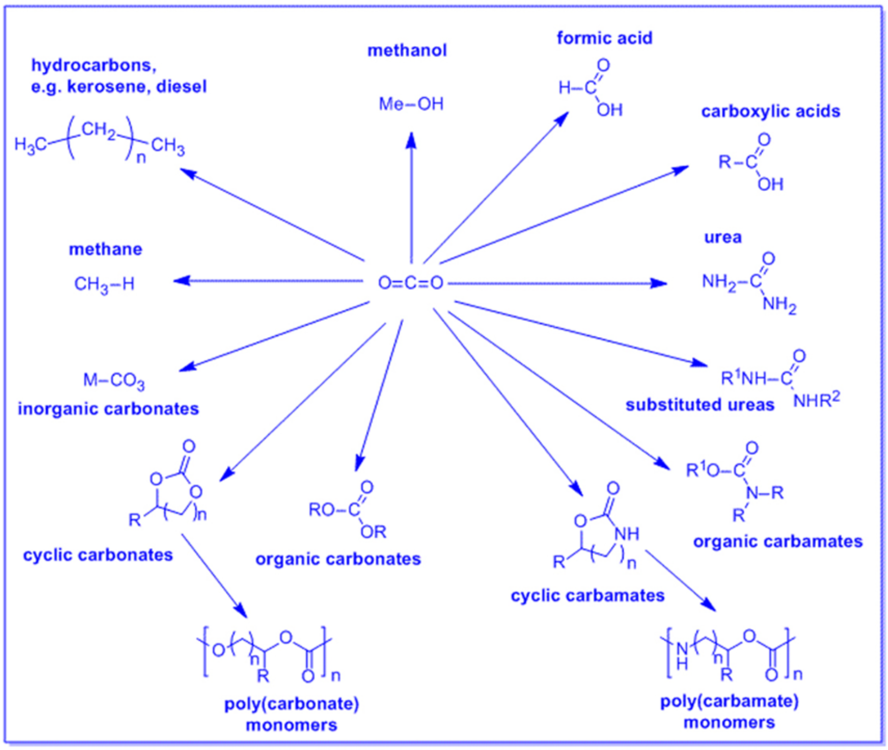

*Figure 11 – $CO_2$ to chemicals. Jansen, D.; Styring, P.; de Coninck, H.; Reith, H.; Armstrong, K. (2011). Carbon Capture and Utilisation in the Green Economy*[41]

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[41] http://co2chem.co.uk/wp-content/uploads/2012/06/CCU%20in%20the%20green%20economy%20report.pdf (online) accessed April 2016

Using $CO_2$ as a renewable feedstock in the production of polymers is an advancing technology with strong innovation potential. Materials can be made by direct polymerization of $CO_2$ or by polymerizing $CO_2$-sourced monomers. Much research has been focused on the development of efficient catalysts to grow the polymer chain. Small scale production is being deployed by both Covestro[42] and Novomer[43] to produce polyols from $CO_2$ for the production of polyurethane foams for use in furniture and mattresses. Adhesives, resins and fillers derived from $CO_2$ are also reaching the construction materials market. The $CO_2$ based-polymers produced contain 20-50% $CO_2$ by mass and although are not carbon negative, do give emission reductions greater than 20% over traditional polymer production.

The use of cyclic carbonates is expanding due to their uses as electrolytes for lithium ion batteries, as solvents, constituents for oils and paints and as an intermediate for polymer synthesis. A great deal of research is being undertaken to bring cyclic carbonates made from $CO_2$ to market due to the increasing potential market capacity; research is primarily focused on catalysis improvement to allow the process to operate as close to room temperature and pressure as possible to decrease energy costs. The production of cyclic carbonates from $CO_2$ is highly atom efficient and can lead to the removal of phosgene from the production process.

Hydrocarbons can be carboxylated by inserting $CO_2$ into the C-H bond to give a range of carbonic acids, esters and hetrocycles. Much of this research is still exploratory, however the high value and market potential of the fine chemicals produced, gives a driving force for further research and innovation.

As the majority of specialist chemicals derived from $CO_2$ are still at early research stages it is recommended that a watching brief be kept to observe how the sector develops in the near future. A focus on bringing together the academic and industrial community in Scotland under an umbrella of $CO_2$ utilisation will help to develop links in the area. In particular, developing links between the Industrial Biotechnology sector, the hydrogen sector and the $CO_2$ utilisation sector is likely to prove fruitful *e.g.* in linking bio-refineries with $CO_2$ utilisation.

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[42] http://www.covestro.de/en/Projects-and-Cooperations/CO2-Project (online) accessed April 2016

[43] http://www.novomer.com/ (online) accessed April 2016

## 5.6 Inorganic Fertiliser

Scotland has a proportionally greater task to decarbonise its agricultural sector than the UK as a whole, as it makes up a significantly greater part of its overall greenhouse gas emissions[44,45] at 17% compared to the UK's 9%[46]. As other sectors in Scotland's economy undergo decarbonisation more rapidly than the agricultural sector *e.g.* the power sector with the recent closure of Longannet, the percentage proportion of emissions from the agriculture sector will increase. This suggests a need for increased focus and innovation for the agriculture sector to play its part in the long-term decarbonisation of Scotland. One area of innovation is in the utilisation of $CO_2$ from the food and drink sector in the production of inorganic fertilisers.

Scotland currently imports all of its inorganic fertiliser demand, mainly from England, Norway and the EU. The scale of these imports in tonnage terms has been calculated from the British Survey of Fertiliser Practice 2014[47] at circa 680,000 tonnes for 2014. This would equate to imports with a value of £68 million for each £100 of average sale price. In order to place an order of magnitude financial value on the annual Scottish fertiliser market; taking an average sale price across the different inorganic fertiliser products of £300 per tonne[48] for the 680,000 tonnes in 2014 would suggest Scotland imported circa **£200 million of inorganic fertiliser in 2014**. The complexity of the fertiliser market requires additional research to understand the value of the market in much greater detail, as well as a greater understanding of the decisions to choose particular types of fertiliser over others.

$CO_2$ can be utilised to produce a pelletised carbonate type fertiliser that can be spread on fields with existing farm machinery. CCm Research[49] is a UK based technology SME company that is entering the market with a process that uses locally sourced organic fibrous materials to bind with $CO_2$ to produce a fertiliser and soil conditioner. The CCm process captures $CO_2$ from either post combustion exhaust streams or more concentrated sources of $CO_2$ using a high surface area cellulosic ammonium material. This material is incorporated alongside the captured $CO_2$ in the fertiliser, which can help to increase the amount of organic carbon in the soil. CCm Research have developed their process through a pilot project using cellulosic material and $CO_2$ from a municipal solid waste energy recovery plant, but feel the process technology is fully transferable to other areas where cellulosic streams are co-located with sources of $CO_2$.

For this report, CCm Research were asked to supply a broad indication of the material inputs for a distillery that produces **10 million litres** of alcohol each year. The values were calculated on having a $CO_2$ supply of **7,400 tonnes per annum** from the fermentation of malted barley.

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[44] pp8, Scottish emissions targets 2028 – 2032, Committee on Climate Change, March 2016

[45] Bell,M.J., Cloy,J.M. & Rees,R.M. 2014. The true extent of agriculture's contribution to national greenhouse gas emissions. Environmental Science & Policy, 39, 1-12.

[46] Figure 3.7, pp33, Scottish emissions targets 2028 – 2032, Committee on Climate Change, March 2016

[47] ISBN 978-0-99297-350-6, https://www.gov.uk/government/collections/fertiliser-usage (online) accessed April 2016

[48] http://dairy.ahdb.org.uk/market-information/farm-expenses/fertiliser-prices/uk-fertiliser-prices/ (online) accessed April 2016

[49] http://www.ccmresearch.co.uk/intro.html (online) accessed April 2016

CCm Research indicated their process would need the following material inputs to utilise >95% of the $CO_2$ produced by the fermentation process each year.

| Item | Proportion by mass | Tonnes per annum |
|---|---|---|
| **Fibre** | 25% | 6000 |
| **Ammonia** | 20% | 4800 |
| **Calcium Nitrate** | 5% | 1200 |
| **Potash** | 10% | 2400 |
| **Phosphate** | 10% | 2400 |
| **$CO_2$** | 30% | 7200 |
| | | |
| | Fertiliser Output | 24000 |

*Table 5 – Material inputs to CCm Research fertiliser process for **10 million litres** per annum Whisky distillery that has a capture ready $CO_2$ resource of **7400 tonnes per annum**.*

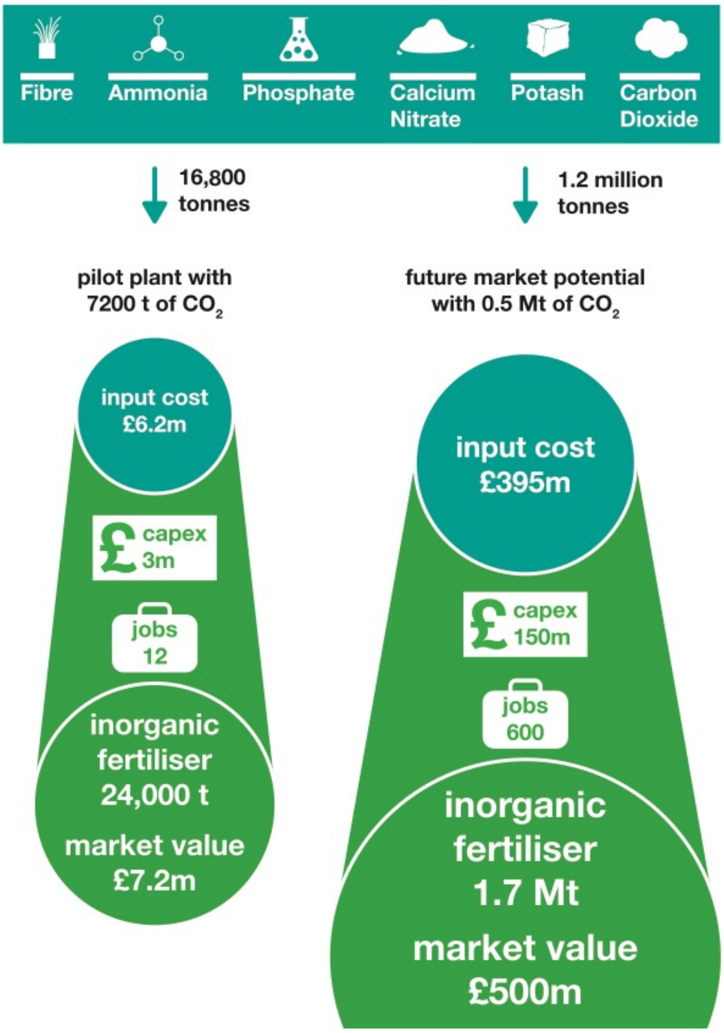

*Figure 12 – Graphic of scaled up potential of 500,000 tonnes per annum of biogenic $CO_2$ feedstock to fertiliser*

The **6000 tonnes** of fibre would be locally sourced and potentially on site, as a partial use of the distiller's malt draff by-product from the distilling process, and the **2400 tonnes** of ammonia would also be locally sourced where possible. This would produce **24000 tonnes** of compound fertiliser with a nominal N, P, K specification of 20,10,10 as a pelletised product. The process also produces low-grade heat, which could be utilised to offset other existing low-grade heating needs on the site or potentially for other higher value areas.

At a rate of **£300 a tonne** (which was the rate used to calculate the order of magnitude for the value of the Scottish fertiliser market), this would equate to a revenue of **£7.2 million per annum**. If the ammonia is able to be produced locally using low carbon sources to produce the hydrogen and the nitrogen, rather than the large-scale fossil fuel derived ammonia production routes, then the fertiliser would have an even lower overall carbon footprint. A greater understanding of the available sources of ammonia in Scotland would be helpful. Local sustainable ammonia production may be an area for Scotland to consider in its membership of the European 6 model demonstrator regions for sustainable chemical production.

A recent report that focussed on the land based sector in the North East of Scotland[50] highlights a number of specific challenges for the region such as the plateau of cereal yields and a long-term concern about the loss of soil organic matter on heavily cropped land. The report also identifies the poor links between the sector and R & D programmes and organisations. The diversification of the farming sector into other biomass areas such as woodland is noted, and the above average uptake of wind based renewable energy through the Feed-In-Tariff scheme is suggested as an indication of the willingness to adapt and invest in additional revenue streams, and the entrepreneurial nature of the sector.

The by-product of fermentation in the Whisky sector is estimated to provide **500,000 tonnes per annum of high-quality biogenic $CO_2$**, and the concept of providing a fully circular supply chain from barley -> fermentation -> $CO_2$ -> fertiliser -> barley provides a highly appealing narrative. This is an area that requires more knowledge to understand the practical and financial challenges of utilising this high-purity biogenic $CO_2$ resource. The demand for fertiliser is highly seasonal, as displayed in Figure 13, so supply chains would need to store sizeable amounts of fertiliser in order to match the feedstock production of the biogenic $CO_2$ resource from the distillery sector, which is felt to be reasonably constant throughout the year.

**Given the nature of the following factors from the Agricultural sector in Scotland:**

- **The particular challenge in decarbonizing the sector due to its size in relation to overall Scottish emissions**
- **The local sources of biogenic carbon that the sector produces**
- **A willingness of the sector to adapt and invest in other novel sources of revenue**
- **The poor coupling between the sector and R & D programmes and organisations**

**It is recommended that the agriculture sector should be a focus for near-term investment in research, development and deployment for $CO_2$ utilisation in Scotland.**

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[50] http://www.aberdeenshire.gov.uk/media/15921/land-based-sector-web.pdf (online) accessed March 2016

Biogenic $CO_2$ derived fertilisers align with Scotland's ambition to be a world leader in Green farming by providing a circular use of biogenic carbon coupled with low carbon energy inputs that could also potentially increase the soil organic matter too. It would provide a lower-carbon product into the food and drink sector that may have additional benefits throughout the supply chain.

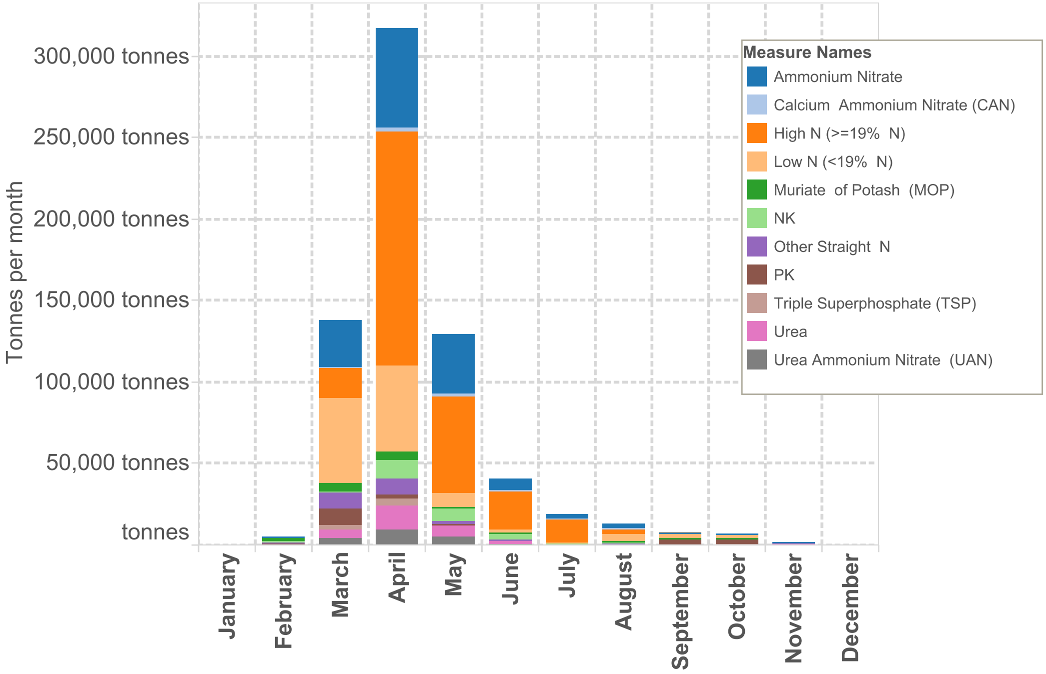

*Figure 13 – Fertiliser demand in Scotland by type and by month, calculated from tables EW3.3 and GB3.3, British Survey of Fertiliser Practice 2014*[51]

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[51] ISBN 978-0-99297-350-6, https://www.gov.uk/government/collections/fertiliser-usage (online) accessed April 2016

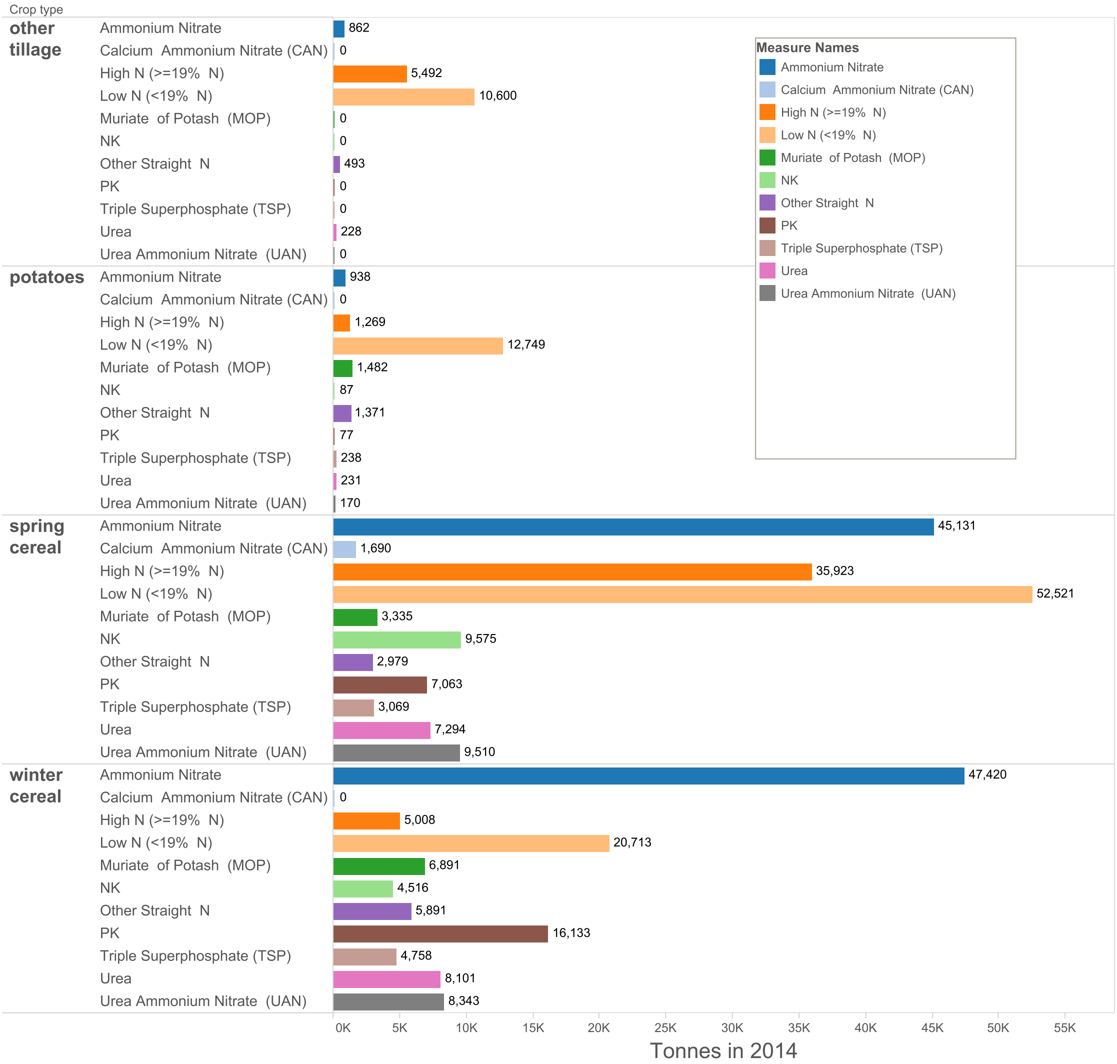

*Figure 14 – Fertiliser demand in Scotland by fertiliser type and by crop type, calculated from tables EW3.3 and GB3.3, British Survey of Fertiliser Practice 2014*[52]

The number of different types of fertiliser suggests differing needs from the agricultural sector (Figure 14). The factors influencing the choice of inorganic fertiliser by the agricultural sector is important to understand in greater detail and the James Hutton Institute and Scotland's Rural College are organisations that Scottish Enterprise should seek initial advice from in this regard.

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[52] ISBN 978-0-99297-350-6, https://www.gov.uk/government/collections/fertiliser-usage (online) accessed April 2016

As inorganic fertiliser is imported, the emissions for the production of the fertiliser would appear in the statistics of the country of production, not in Scotland's statistics. However, the release of $N_2O$ emissions from soils[53] with inorganic fertiliser does show up in Scotland's emissions through the use of emissions factors for $N_2O$. Reducing the carbon intensity of the production of inorganic fertilisers is one method to reduce the emissions impact of these fertilisers, and increasing the nitrogen use efficiency of the fertiliser is another.

*Nitrous oxide ($N_2O$) is a greenhouse gas which contributes to global warming and climate change. $N_2O$ emissions accounted for about 5% of the UK's greenhouse gas emissions in 2013.* ***Agriculture is the largest source of $N_2O$ emissions in the UK****. Around 79% of $N_2O$ emissions are produced by agriculture, and around 88% of this is from soils, particularly as a result of fertiliser application and leaching. The UK target under the Kyoto Protocol was to reduce greenhouse gas emissions to 12.5% less than 1990 baseline levels by 2008 to 2012 (averaged over 5 years).*[54]

$N_2O$ has a 100-year Global Warming Potential that is 298 greater than $CO_2$.

A recommendation of this section is for Scottish Enterprise to commission a more detailed study on the supply and demand of inorganic fertiliser in Scotland. This could provide greater detail of the type, scale, value and geographical demand of inorganic fertilisers in Scotland, into the type and scale of biogenic sources of $CO_2$ in the agriculture and food and drink supply chains, and into the type and sources of potential ammonia supply in Scotland.

A further recommendation is to facilitate a medium-term field study of the use of cellulosic carbonate fertilisers on microbial activity on a range of soils in Scotland, how this impacts the nitrogen use efficiency and release of $N_2O$ and how this impacts the retention of organic matter in soils under a range of differing conditions. This should have a particular focus on the soils typically used to grow spring barley for the Whisky industry.

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[53] Hinton,N.J., Cloy,J.M., Bell,M.J., Chadwick,D.R., Topp,C.F.E. & Rees,R.M. 2015. Managing fertiliser nitrogen to reduce nitrous oxide emissions and emission intensities from a cultivated Cambisol in Scotland. Geoderma Regional, 4, 55-65.

[54] Agri-indicator DD2: Nitrous Oxide Emissions – indicator fact sheet https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/408685/agindicator-dd2-03mar15.pdf (online) accessed April 2016

## 5.7 Mineralisation of $CO_2$

The carbonation of minerals is based on the reaction of $CO_2$ with metal oxide bearing minerals such as silicates of calcium and magnesium to form inert carbonates. This happens as a natural process over geological time scales by the weathering of rock, and forms a major part of the earth's long-term carbon cycle to remove and fix $CO_2$ from the atmosphere.

There are two broad areas of $CO_2$ mineralisation that can be characterised by the type of source material to be carbonated.

- Mineral carbonation where $CO_2$ is reacted with calcium or magnesium silicate minerals to form inert calcium or magnesium carbonates.
- Industrial waste or contaminated soil carbonation, where $CO_2$ is reacted to treat certain industrial wastes and soils.

There are several advantages to mineral carbonation such as the creation of a mineral form of carbon that serves to lock carbon out of the atmosphere over the long-term in a stable, leakage free manner. The large potential sources of rock are also an advantage as are the exothermic nature of the carbonation reactions themselves which produce significant amounts of heat. Mineral carbonation can also potentially use $CO_2$ flue streams with little pre-treatment, as the mineralisation step itself is the capture process.

The mineral carbonation route is technically feasible but commercially challenging due to a combination of the slow speed of carbonation reactions and the quantity of source rock required compared to the amount of $CO_2$ that can be fixed, which is at least several tonnes[55] of rock per tonne of $CO_2$. Research is ongoing into methods to accelerate the reaction and reduce the energy inputs needed to do so, by *e.g.* exploiting the heat of the reaction. If geoengineering options are required in the future to remove significant quantities of $CO_2$ from the atmosphere, then this mineral carbonation route may be one of the simpler avenues, as it mimics a natural weathering cycle.

In contrast to mineral carbonation, the carbonation of industrial wastes is currently commercial, with two plants producing a total of >120,000 tonnes of mineralised product per annum. Carbonating industrial wastes can bring advantages to the management of the industrial waste stream in terms of its further handling, eventual disposal, or potentially even lead to a marketable product. As industrial wastes are within the scope of the waste regulations they can provide a potential revenue stream that follows the waste feedstock too, which is one of the reasons for this area's commercial viability.

In the UK, Carbon8[56] is using accelerated carbonation to treat waste to produce a lightweight manufactured carbonated aggregate for use in concrete blocks. The waste currently processed in its two UK plants is Municipal Solid Waste air pollution control residues. Production of aggregates using this waste stream is expected to increase to circa. **500,000 tpa** (capable of capturing greater than **50,000 tpa** of $CO_2$) with the building of 3 more UK plants by 2019. As the technology can be applied to a variety of waste streams and to contaminated soils, further

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[55] IPCC, 2005 - Bert Metz, Ogunlade Davidson, Heleen de Coninck, Manuela Loos and Leo Meyer (Eds.). Cambridge University Press, UK. Chapter 7 Mineral Carbonation and industrial uses of CO2. http://ipcc.ch/pdf/special-reports/srccs/srccs_chapter7.pdf (online) accessed April 2016

[56] http://www.c8s.co.uk/ (online) accessed 2016

commercial development opportunities are anticipated. Additional benefits realised from carbonating waste are the protection of natural mineral resources and the diversion of significant volumes of waste from landfill and a sustainable contribution to the circular economy.

Advice should be sought from SEPA to find out the level of knowledge surrounding the type, scale and location of industrial wastes and contaminated soils in Scotland and in particular whether certain wastes could be disposed of in Scotland after treatment, rather than having to be transported to specialised landfill sites in England. This would help to establish the scale of various wastes and contaminated soils in Scotland that could potentially benefit from this type of treatment.

# 6 Could $CO_2$ utilisation help with Scotland's wider policies?

## 6.1 Scotland's agricultural sector

As detailed in Section 5.6 on inorganic fertilisers, the Scottish agricultural sector faces several challenges in terms of decarbonisation, diversification and the improvement of soil quality. Inorganic fertiliser production from renewable energy sources and biogenic sources of $CO_2$ are supportive of overarching policies to tackle these challenges.

## 6.2 Scotland's Industrial Biotechnology sector

The growth of the Industrial Biotechnology (IB) sector in Scotland via a successful implementation of the IB strategy, is thought to be positive for the CCU sector for a number of reasons. The likelihood is that increased IB activity will lead to further sources of biogenic $CO_2$ becoming available as a resource, *e.g.* Celtic Renewables[57]. It is also likely that parts of the IB value chain and the $CO_2$ utilisation value chain will overlap, as biological methods of processing $CO_2$ into products become developed and deployed. This report has highlighted the non-biological routes of $CO_2$ utilisation rather than biological routes such as Joule Unlimited[58], Algenol[59], Sapphire Energy[60], Cellana[61] algal routes, as these are not thought to be suitable for Scotland's reduced solar resource. However, IB routes that are non-algal based such as the gas fermentation technology being developed by the US firm Lanzatech[62] that uses microbes should be of interest to Scotland's IB and wider industrial communities.

## 6.3 Scotland's island and rural communities?

Carbon emissions from point sources in Scotland's island and rural communities are unlikely to be connected directly to a CCS network, as the distances to be covered versus the volume of $CO_2$ captured are not economic. Although there are few point sources of $CO_2$ on the SPRI database in these areas, the number or type of $CO_2$ emitters that are below the threshold (10,000 tonnes per annum) is not well understood.

Fuel for heating and transport can be disproportionally expensive in island and rural communities due the transport costs of liquid and LNG fuel to these locations from refineries. A recent report into the Economic Opportunities of Renewable Energy for Scottish Island Communities[63] suggests significant levels of curtailment already happening within Island and Rural communities *e.g.* Orkney's Active Network Management area. The report states that

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[57] http://www.celtic-renewables.com/ (online) accessed April 2016

[58] http://www.jouleunlimited.com/ (online) accessed April 2016

[59] http://www.algenol.com/ (online) accessed April 2016

[60] http://www.sapphireenergy.com/ (online) accessed 2016

[61] http://cellana.com/ (online) accessed April 2016

[62] http://www.lanzatech.com/ (online) accessed April 2016

[63] http://www.gov.scot/Resource/0049/00495193.pdf (online) accessed April 2016

increased network capacity is the 'primary' method to alleviate curtailment, but a number of other methods are being considered too, including *'diverting the excess power'* to meet heating or transport demands, or to produce hydrogen. Orkney has a developing Hydrogen Economic Strategy, that already has $CO_2$ utilisation in the form of liquid hydrocarbon and production of urea[64] in the draft version.

For remote areas that have an adequate renewable resource, the ability to change energy vectors from electricity to chemical forms of energy such as hydrogen, methane, methanol, or liquid fuels provides an ability to store electricity at various times of potential curtailment from network constraints. These different forms of energy do not need to be transformed back to electricity, as they can offset or provide the energy requirements for other demands such as heating and transport. This is not likely to be the most efficient path to provide the energy requirements of a final energy demand (more energy transformations mean more efficiency losses), but the ability to use existing infrastructure such as liquid fuel tanks, LNG tanks, liquid fuel or LNG boilers, internal combustion engines and burners is appealing from a standpoint of public acceptability and sunk investment costs. **The focus on efficiency should not always be the main factor in deciding a technology for storing energy, especially in areas subject higher levels of curtailment.**

As described in the previous chapter, the combination of hydrogen from electrolysis with a suitable source of $CO_2$ can provide a range of different hydrocarbons or methanol.

**The challenge is to understand where the sources of $CO_2$ exist in island and rural communities in greater detail and whether the $CO_2$ utilisation technologies can be scaled to suit these.**

*'Remote and island communities are often located in areas that are particularly suitable for renewable power generation (i.e. wind and marine power). Investment in renewable generation could therefore provide local benefits in terms of employment and profit sharing, in particular with community and off-grid schemes. Projects such as the Northern Isles New Energy Solutions could help to deliver a secure, affordable and reliable energy system to islands. To realise the full potential of renewable generation in island communities, increased interconnection is likely to be needed to the larger electricity markets on the mainland.'*[65]

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[64] http://www.orkney.gov.uk/Files/Committees-and-Agendas/Development%20and%20Infrastructure/2015/10-09-2015/I11_App1_Draft_Orkney_Hydrogen_Economic_Strategy.pdf (online) accessed April 2016

[65] pp44, Scottish emissions targets 2028 – 2032, Committee on Climate Change, March 2016

## 6.4 Scotland’s community ownership of energy

A recent area of significant activity for the Scottish Government concerns not only the provision of low carbon energy (principally electricity and heat), but importantly also the ownership and of such technologies and projects. Steps have been taken to encourage ‘Community energy’ and ‘Locally-owned energy’, including the establishment of a target by 2020 for an installed capacity of 500MW of community and locally-owned energy in Scotland[66]. As well as financial support for the sector, there are attempts to understand the barriers preventing such groups from increasing their involvement in energy. The Energy Saving Trust’s October 2015 report[67] states ‘The 500MW target has been reached, with an estimated minimum of 508MW of community and locally owned renewable energy capacity operational in Scotland as at September 2015. This 508MW of total capacity is split between approximately: 301MW of electrical capacity (MWe); 199MW of thermal (heat) capacity (MWth); 7MW of combined heat and power (CHP) capacity.’

Additionally, there is a clear and growing policy interest in the concept of ‘local energy economies’, or ‘a localised approach to energy provision’[68]. These are ‘the concept of integrating low carbon energy sources in local energy systems and supply chains in a way that maximises system efficiency and adds value for local stakeholders’[69]. The added value from such interventions – currently being examined in pilot projects - reflect the crucial role that changing the pattern of energy provision might play in future energy scenarios at local levels. These include: improving shortening the value chain between production and consumption for energy, overcoming grid constraints, improving the resilience of the local supply chain for energy and providing or improving local skills or employment.

The level of ambition for community owned energy generation is likely to lead to increased targets for the area. Being able to utilise more of the energy at a local level provides additional benefits to community owned energy, by adding value for local stakeholders rather than merely exporting the electricity to another area to add value elsewhere or being constrained off the grid. $CO_2$ utilisation offers one of a number of potential routes to add value to electricity and local resources of $CO_2$ and local demands for various products and services would impact which potential route would be of most interest.

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[66] http://www.gov.scot/Topics/Business-Industry/Energy/Energy-sources/19185/Communities (online) accessed 2016

[67] http://www.energysavingtrust.org.uk/community-energy-reports - October 2015

[68] http://www.gov.scot/Resource/0049/00494812.pdf, page 6. (online) accessed 2016

[69] http://www.gov.scot/Resource/0048/00485122.pdf, page 35. (online) accessed 2016

## 6.5 Scotland's low carbon economy

A new Strategic Priority – *'Transition to a low carbon economy'* – was introduced in the Government Economic Strategy in 2011[70], while the 2015 update discussed the importance of investment and the labour market supporting the economic opportunities in the low carbon economy[71] as well as noting that *'sustainable economic growth rests on a requirement to make the transition to a more resource efficient, low carbon economy'*[72].

The vision of a low carbon economy – although principally motivated by environmental concerns, is intimately linked to economic objectives for Scotland as a whole and shown in Figure 15. The central purpose of the Scottish Government since 2007 has been *'to create a more successful country, with opportunities for all of Scotland to flourish, through increasing sustainable economic growth'.*

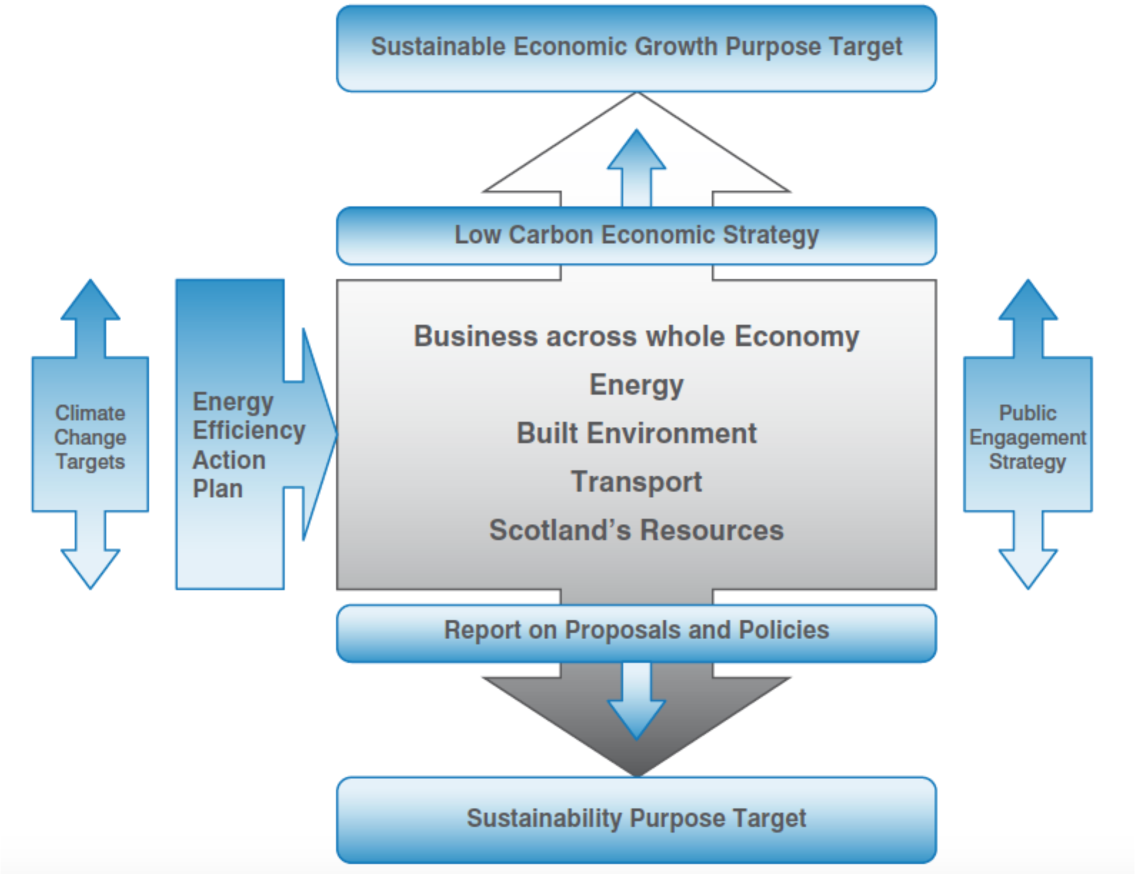

*Figure 15 - Low carbon economic strategy* Source*: Scottish Government,* Low carbon economic strategy, *November 2010*

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[70] The 2011 Government Economic Strategy - http://www.gov.scot/resource/doc/357756/0120893.pdf (page 5) (online) accessed April 2016

[71] 'Our ambition [as set out in the SCCA]… represents a fundamental transition of all sectors of the economy and a long-term strategy for economic growth: reducing the cost to the Scottish economy of climate change, while maximising opportunities to export our technology innovations and knowledge as other economies make their own low carbon transition' (p. 45).

[72] The 2015 Government Economic Strategy - http://www.gov.scot/Resource/0047/00472389.pdf (online) accessed 2016

Although $CO_2$ utilisation is not primarily aimed at the mitigation of $CO_2$, it should help to decouple Scotland's emissions from economic activity, and therefore help with the transition to a lower carbon economy. In this regard, it is important to understand the life cycle analysis of various $CO_2$ utilisation products and processes, and also the sources of the carbon. We will still require products that contain carbon in the future, but the source of the carbon and what happens to it at the product end-of-life need to profoundly change.

## 6.6 Scotland's circular economy transition.

The UK Waste and Resources Action Programme (WRAP) defines the circular economy as *'an alternative to a traditional linear economy (make, use, dispose) in which we keep resources in use for as long as possible, extract the maximum value from them whilst in use, then recover and regenerate products and materials at the end of each service life'*.[73] WRAP illustrate this concept using Figure 16.

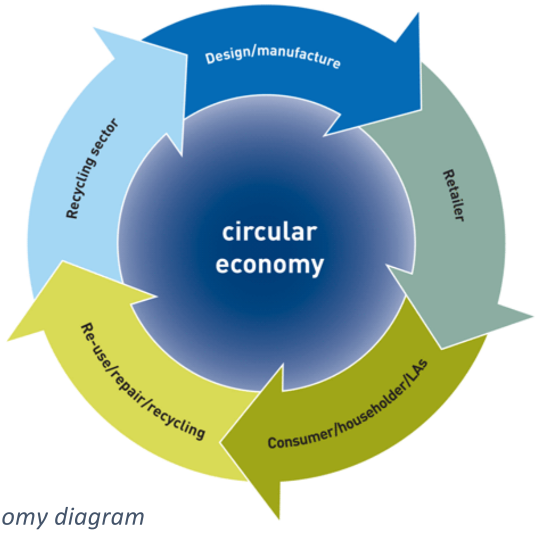

*Figure 16 - WRAP circular economy diagram*

The EU action plan for a circular economy, titled 'Closing the Loop', similarly focuses on physical waste, treatment options and recycling through entire product and material life-cycles.[74] The 2015 Club of Rome report on 'The Circular Economy and Benefits for Society' also share a similar focus on extending product and material life cycles.[75]

Where carbon has been associated with circular economy discussions, this has tended to be in terms of carbon footprint implications of changes in material consumption and physical waste generation. For example, the work of Zero Waste Scotland's (2011) on 'The Scottish Carbon Metric' linking to carbon impacts of the life cycle waste impacts of different materials and products.[76] That is, it retains the linear economy relationship for carbon, albeit linking to the

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[73] http://www.wrap.org.uk/content/wrap-and-circular-economy (online) accessed 2016

[74] http://ec.europa.eu/environment/circular-economy/index_en.htm (online) accessed 2016

[75] http://www.clubofrome.org/cms/wp-content/uploads/2015/04/Final-version-Swedish-Study-13-04-15-till-tryck-ny.pdf (online) accessed 2016

[76] The Scottish carbon metric report can be downloaded at

impacts of resource efficiency and/or recycling activities where more of a circular economy relationship is established. The utilisation of $CO_2$ aligns with circular economy aims to keep resources in use as long as possible, however, legally $CO_2$ is not classed as a waste material.

## 6.7 Scotland's CCS sector

The main driver for CCS is climate change. In Scotland, there is a focus to decarbonise the energy system by 2050, as set out in the Climate Change (Scotland) Act 2009[77].

The Scottish government are promoting a whole system view to decarbonise heat and transport, by considering the use of electricity and energy demand reductions.

Pale Blue Dot Energy[78] and SCCS[79],[80] set out a vision for a low carbon energy and industrial sector in Scotland, with an initial focus on the Grangemouth area. SCCS refer to this as an *East Scotland Low Carbon Zone*.

This vision includes leveraging existing pipeline infrastructure to kick-start a $CO_2$ transportation network, linking up to the world class $CO_2$ storage locations in the North Sea, with future potential $CO_2$ enhanced oil recovery ($CO_2$-EOR). Scotland's oil and gas expertise and well-established supply chain can support the engineering and development required.

In addition, Scotland could lead the UK in hydrogen production with CCS (pre-combustion capture or steam reformation of methane with CCS) for use directly in transport, or combined with $CO_2$ to create a syngas that can be transformed into a wide range of hydrocarbons. Hydrogen also offers the potential to link the electricity network with the gas grid by using an electrolysis route to generate hydrogen, which can be then be transported and stored within the existing gas grid. The amount of hydrogen allowed in the natural gas grid is however limited due to defined limits governed by safety concerns that are set in legislation. Hydrogen is also used in many industrial processes, *e.g.* refining.

Within Scotland, the Grangemouth area is of strategic importance to kick-start an industrial and power CCS cluster and $CO_2$ transportation network, due to the close proximity of existing and planned emissions sources to existing pipelines. One key existing pipeline is Feeder 10 that has

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http://www.zerowastescotland.org.uk/sites/default/files/The%20Scottish%20Carbon%20Metric.pdf. The most recent report by ZWS on 'the Carbon Impacts of the Circular Economy' was published in 2015 and can be downloaded at

http://www.zerowastescotland.org.uk/sites/default/files/CIoCE%20Technical%20Report%20-%20FINAL%20-%2015.06.15.pdf. (online) accessed April 2016

[77] Climate Change (Scotland) Act, 2009 http://www.legislation.gov.uk/asp/2009/12/contents (online) accessed April 2016

[78] PBDE, 2014. 'Low Carbon Scotland: A strategy to decarbonize the industrial and energy sectors'. Summarized in: http://www.pale-blu.com/perspectives/low carbon-scotland-the-role-of-ccs-to-decarbonise-industry-and-energy

[79] SCCS, 2016. 'Scottish CO2 Hub – A Unique Opportunity for the UK' http://www.sccs.org.uk/images/expertise/reports/working-papers/wp-2016-01.pdf (online) accessed April 2016

[80] SCCS, 2016. 'Achieving a low carbon society: CCS expertise and opportunity in the UK.' SCCS Conference 2015 Report. http://www.sccs.org.uk/images/expertise/reports/low carbon-society/downloads/Conference-2015-report.pdf (online) accessed April 2016

a capacity of **8-10 million tonnes per annum**, which links Grangemouth directly with St Fergus and ultimately to offshore storage sites or $CO_2$-EOR in the North Sea. Feeder 10 is a high-pressure gas-grid pipeline built to take natural gas from St Fergus to Grangemouth, but which is capable of being re-serviced for $CO_2$ transportation.

Many point sources of emissions in Figure 2 are in close proximity to Feeder 10. These, along with the Caledonia Clean Energy Project[81] could be used to kick-start a $CO_2$ capture hub and transportation network from Grangemouth.

As described in Chapter 5 on 'What Scotland could do with its $CO_2$ resource' there are several opportunities for $CO_2$ utilisation that do not depend on the development of a CCS infrastructure, and clearly some that would benefit from CCS development too.

**Many opportunities exist for $CO_2$ utilisation in isolation from full chain CCS; there is no need to wait on CCS infrastructure being available to progress certain $CO_2$ utilisation processes in Scotland.**

**In the longer-term when significant markets for CCU products have developed, Scotland could create significant competitive advantage by becoming a world leader in establishing and growing a $CO_2$ utilisation market off the back of relatively simple CCS infrastructure, in part built from existing oil and gas assets. Grangemouth is clearly the location for any strategic aspiration to create a CCU market of scale in Scotland, which has a focus on satisfying an international demand for low carbon fuels and chemical feedstocks.**

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[81] http://www.summitpower.com/projects/carbon-capture/ (online) accessed April 2016

# 7 Scotland's future energy systems

Many $CO_2$ utilisation processes benefit from access to sources of lower cost low carbon energy sources, and in the case of making fuels from $CO_2$ it is a prerequisite. Scotland's future energy systems are therefore of great importance to the development of $CO_2$ utilisation, but the reverse is true to some extent too. Hydrogen for $CO_2$ utilisation from hydrogen electrolysis can provide certain benefits to energy systems in terms of system flexibility via a dispatchable demand, and the potential to store significant levels of energy too.

The Scottish Government's vision of its low carbon future is that *'by 2050 Scotland will have a highly sustainable and prosperous economy [and be] a major player and beneficiary in the development of global low carbon markets'*[82].

The Scottish Government has timetabled a major refresh of its energy policy strategy and targets in 2016. Feeding into this will be the recommendations from the Committee on Climate Change's (CCC) report on Scottish Emission targets from 2028 – 2032[83]. The CCC report takes into account the increasing knowledge of emissions from various sectors, and also the changing political environment after the COP21 in Paris in late 2015. The energy policy refresh is also likely to use a **whole systems** approach to the energy sector that considers the interaction between the demand from heat, transport fuels and electricity, and also a more localised focus on resilience.

These are areas where $CO_2$ technologies can help, as transforming electricity into carbon based energy vectors such as methane, methanol or synthetic hydrocarbons could help to provide a use for electricity at times of potential oversupply. This can help to balance the electrical grid over shorter timescales, and also allows heat and certain transport demands to be **partially** satisfied over longer timescales. It could also provide a certain amount of system resilience at a local level in terms of more local self-sufficiency of energy and a reduction in energy imports – not just of electricity.

The CCC report contains the following highlights:

- *The Committee recommends that the Scottish annual targets are set to require a 61% reduction in the Scottish emission account in 2030 relative to 1990. That would keep Scotland on track to its 2050 target to reduce emissions by at least 80% on 1990 levels by 2050. In line with Scottish ambition, this goes further than the reduction we have recommended in our fifth carbon budget advice for the UK as a whole.*
- *The Committee recommends that Scotland aims to meet these targets through domestic action, without recourse to purchase of emissions credits.'*

Due to advances in the science surrounding emissions from the agricultural, land use and waste sectors, Scottish baseline emissions in 1990 have been recalculated and significantly increased. The Committee has therefore recommended the nearer term targets to 2020 are themselves recalibrated with an increase of the target to reduce emissions by 47% rather than the previous value of 42%. **Although at this stage these are just recommendations, it is anticipated that the**

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[82] Scottish Government (2010), 'Low Carbon Economic Strategy', http://www.gov.scot/Resource/Doc/331364/0107855.pdf, page 6.

[83] Scottish emissions targets 2028 – 2032, Committee on Climate Change, March 2016

**policy refresh in Scotland will adjust to take account of these in order that Scotland continues to lead the UK in its ambition to decarbonise its economy.**

The Committee also state that:

- *Electricity generation: reducing emissions intensity from over 200g to 10-20 $gCO_2/kWh$ by 2030, compared to around 100 $gCO_2/kWh$ for the UK. This would also go beyond Scotland's legislated target of 50 gCO2/kWh, but is achievable given the very large potential for expanding renewable power and the shutdown of coal-fired power*
- *Emissions in the power sector in Scotland were 11.5 million tonnes in 2013 across 51.7 TWh of electricity generation, representing a carbon intensity of generation of $221gCO_2/kWh$.*

A whole systems approach to energy systems is typified by Figure 17 that plots the daily amount of energy that flows through the differing energy networks. This gives a sense of the scale and the seasonality of the demands for heat, transport and electricity.

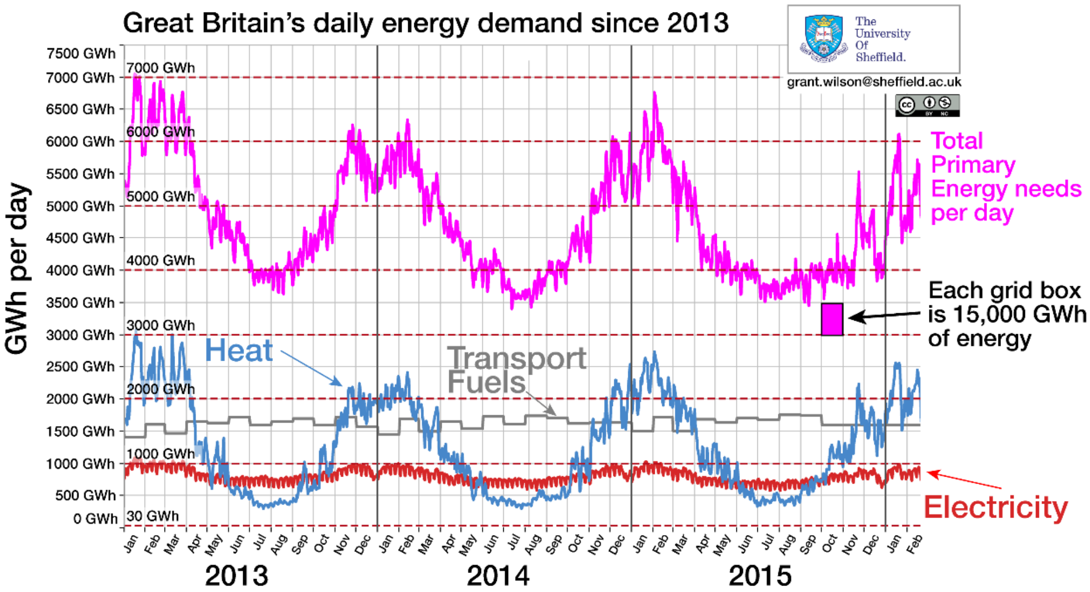

*Figure 17 – Great Britain's energy demands per day*

In 2013 about 54% of Scottish final energy consumption was from heating and 25% from transport, which are recognised as being critical to decarbonisation but have not been the focus; instead the focus has been on the 21% from electricity generation[84].

It can be seen that heat is the greatest source of interseasonal variation in any of the energy demands of Great Britain. This is not surprising as winters are colder than summers and thus the heat demand is greater. What is surprising though, is the sheer scale of the variation in comparison to the variation in electrical demand or the transport demand.

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[84] Figure 2.2 Energy in Scotland 2016, http://www.gov.scot/Resource/0049/00494812.pdf pp31 (online) accessed April 2016

A recommendation of this report is to commission the creation of a diagram with Scottish data, *i.e.* a Scottish version of Figure 17 in order to help understand the seasonal variation of demands in a Scottish context, and promote a whole systems approach to energy systems.

The purple box in Figure 17 (one grid box) is 15,000 GWh, which is the energy equivalent of 1500 Ben Cruachan hydro pumped storage schemes (Figure 18). In terms of interseasonal storage, it is clear from Figure 17 that if TWhs of storage are not available, then the demand has to be satisfied by primary energy suppliers being able to accommodate the variation by increases in production or imports. The sheer scale of the primary energy seasonality suggests that non-fuel forms of storage are not able to fill the gap. Batteries and pumped storage are also the wrong technology choice as they should be used frequently, whereas interseasonal stores of fuels may be charged and discharged potentially only once a year.

*Figure 18 - Cruachan Hydro Pumped Storage Scheme (images from www.visitcruachan.co.uk)*

Future energy systems will continue to need TWhs of stored energy in the form of fuels to call upon as and when required. Therefore, the choice should not be whether future energy systems should have access to significant stores of fuels, but what type of fuels these should be. All types of fuels have advantages and disadvantages in comparison to each other, which is why there are such a wide range of fuels that are currently used. $CO_2$ derived fuels have advantages and disadvantages in comparison to conventional fuels and hydrogen, and these are detailed in Table 6. It is unclear which fuels will come to dominate in the future, but it should be considered that the future may well require a wide range of fuels too, and the choice of these is likely to be governed by the interplay of a number of international and local factors. The choice of fuels in the future may well be as complex as the choice of fuels is today, albeit, they should be low carbon.

| Type of stored fuel | Advantages | Disadvantages |
|---|---|---|
| **Fossil hydrocarbons** | Existing supply chains. Economic to store at bulk and at a distributed level. The energy is already contained in the product. | Carbon emissions; price volatility |
| **Hydrogen from hydrocarbons *e.g.* steam reformation of methane** | Existing supply chains; hydrogen is more expensive to store at a distributed level | Carbon emissions; price volatility |
| **$CO_2$ derived fuels - Synthetic hydrocarbons** | Developing supply chains; economic to store at bulk and at a distributed level. | The energy in the fuel comes from primary electricity, and is likely to be uncompetitive with fossil fuels |
| **Hydrogen from electrolysis** | Hydrogen with a low carbon footprint is possible if the electricity is low carbon | The energy in the fuel comes from primary electricity, and is likely to be uncompetitive with fossil fuels |

*Table 6 – Fuel type advantages and disadvantages*

## 7.1 Longer-term perspectives on energy in Scotland

It is challenging to predict the generation mix in Scotland well beyond the lifetime of the existing electrical generation fleet. What can be done is to examine the direction of travel for different electricity technologies, and the likely scale of their growth over the coming decades. The point of this exercise would be to try to better understand the risk of curtailment due to network congestion. The production of hydrogen for combination with $CO_2$ to create $CO_2$ derived fuels is a method to help alleviate curtailment, as the electrolysis demand to create these fuels could be ramped up and down to match the availability of renewable electricity and the residual load. This would mean that Scotland would make more use of its renewable energy resource within Scotland itself, and would be able to accommodate more renewable generation on the system without increasing its export capacity.

With regards to the major coal and nuclear fleet, the last few years have seen major changes. March 2013 saw the closure of the major coal facility at Cockenzie, while Longannet closed at the end of March 2016. This brings to a close a long association of coal with the power sector in Scotland. However, as mentioned throughout this report, when a CCS infrastructure is developed in Scotland, then that would likely attract interest and investment in new fossil fuel powered generation that would have most of their emissions captured. The Caledonia Clean Energy Project is exploring this option.

It was recently announced by EDF that their plant at Torness – which was due to close in 2023 – has had its lifetime extended out to 2030[85]. Scotland's other nuclear facility at Hunterston B is scheduled to close in 2023, after it had its lifetime extended beyond its initial scheduled closure in 2016. The Scottish Government, while not opposed to lifetime extensions for Scotland's two nuclear facilities, have ruled out any new nuclear development.

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[85] http://www.bbc.co.uk/news/uk-scotland-35581272 (online) accessed 2016

The latest Electricity Generation Policy Statement produced by the Scottish Government is critical here. It sets out the framework for modelling scenarios for Scottish generation mix into the future. The 2013 statement – the most recent – sets out, for example, the necessary scope and boundaries to changes in domestic generation, including the potential from renewable electricity and for CCS, which at that point saw the anticipated retrofitting of existing conventional stations converted to this technology in the period 2025-2030. The refreshed energy policy later in 2016 will provide additional clarity in the generation mixes that Scotland is likely to have in 2020 and beyond.

The existing and potential investment in renewable energy projects as of September 2015 is dominated by one technology: wind (both on-, and off-shore). Figure 19 shows there is significant additional capacity in development across Scotland, with projects either in planning or already consented which now total over 13GW – over a 230% increase over the existing wind generation at the end of 2015 (5,587MW).

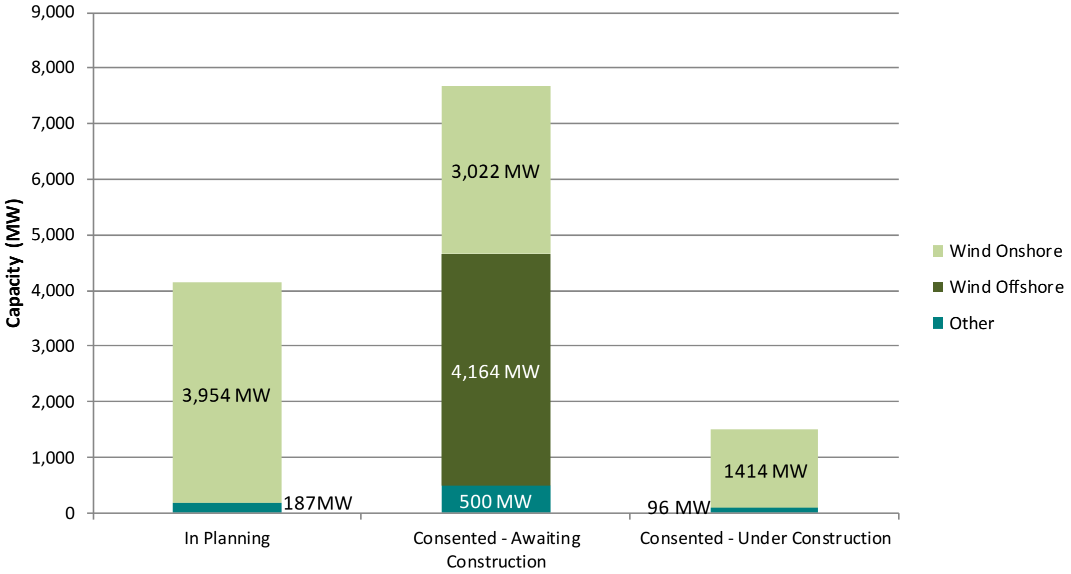

*Figure 19 - Capacity of renewable projects 'in planning' through to 'under construction' (MW), Scotland, as of September 2015 Source: Scottish Government (2016), Energy in Scotland 2016*

Over the long-term, battery and pumped storage will play a very useful role in future Scottish electricity production over hourly, daily and even weekly timeframes in particular given Scotland's growing role for renewable generation and an uncertain future for nuclear post 2030. Demand side response will help too, as will changing demand profiles and having certain transport and heating demands move to the electrical network, but increasing interconnection is still seen as the preferred route to deal with increased amounts of curtailment, by allowing surplus electricity to be exported as now.

## 7.2 Scottish electrical curtailment

The risk of electrical energy generation having to be curtailed is likely to increase until additional sources of demand are able to accommodate the increased levels of generation either locally (before a network constraints) or by increasing the network capacity to be able to export the electrical energy to demands outside the local or regional area.

A recommendation is to understand the potential size of curtailed electricity under differing future energy scenarios in greater detail. This is itself an immersive piece of research that would need close interaction with the Scottish Government's energy team, and would be of interest to a much wider audience than the just the $CO_2$ utilisation sector.

# 8 Understanding the Social Context of $CO_2$ utilisation in Scotland

The future development, deployment and success of $CO_2$ utilisation in Scotland will not be solely governed just by technological advances in the field of $CO_2$ capture and utilisation, or even supportive legislation. Understanding more about the nature of the social context into which the technologies will be introduced should also be considered of fundamental importance. Early steps should be taken to ensure that an appreciation of the factors likely to shape the social and market acceptability of $CO_2$ utilisation in general is developed, and of the associated utilisation options, facilities and infrastructures too.

History tells us that the successful introduction of new industrial technologies is shaped by the opinions of a number of social actors; including politicians, market stakeholders and publics.[86] While not underselling the importance and value of understanding the political and business angles of this triangle of social acceptability; this section stresses primarily the significance and challenges of understanding more about how the opinions of publics – particularly those living in communities earmarked for the introduction of $CO_2$ utilisation facilities.

As publics are able to influence the outcomes of decisions regarding the introduction of new technologies at a number of levels (*i.e.* National, Regional and Household level), engaging with them in discussions about proposals, plans and policies can help foster trust and yield insight, which can improve the decision-making process and deliver more acceptable outcomes for all concerned.

**Crucially, meaningful engagement should occur early in the development cycle of new technology.**[87]

*'Too often, the upstream stages [of engagement] are missed leading to assumptions being made about what the issues are that need addressing, which consequently risks running into conflict or not meeting the market expectations.'*[88]

Appendix 1 - Understanding the Social Context of CO2 utilisation in Scotland' outlines some of the key challenges faced in promoting public engagement with unfamiliar technologies, while simultaneously registering the value that can be derived from meaningful efforts to do so. Broadly, the summary relays the importance of considering matters of publics, project, place, process and practise in shaping opinions of new industrial technologies and in reliably assessing these opinions.

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[86] Wüstenhagen, R., Wolsink, M., & Bürer, M. J., 2007. 'Social acceptance of renewable energy innovation: An introduction to the concept.' Energy policy, 35(5), 2683-2691

[87] https://connect.innovateuk.org/documents/3132264/12254256/Engaging%20People%20with%20Energy%20Technologies

[88] http://erpuk.org/wp-content/uploads/2014/12/ERP-Public-Engagement-Report-May-2014.pdf

Key points detailed in Appendix 1 are:

**Project Factors**

Appreciating more about the subjective factors likely to shape perceptions of risk relating to new industrial technologies, like $CO_2$ utilisation, is important to their successful promotion; as is the selection of trusted communicators to convey information about proposed projects and plans.

**Place factors**

It pays to consider the historical and ongoing connections that publics share with their local environment when identifying locations for potential industrial facility development.

**Process factors**

There is genuine potential value in involving affected publics in the decisions being made about new industrial technologies, particularly at a local level and if properly planned and resourced. There are, however, associated challenges in achieving this in a meaningful sense with new and unfamiliar technologies like $CO_2$ utilisation. One must think carefully about the practise of assessing people's opinions.

**Practise factors**

Considerations of practise are integral to successful assessment of a public's opinions. Poor practises produce poor data and poor data negatively affects the quality of decisions. Consideration should be given now to the formal assessment of emerging opinions to $CO_2$ utilisation in Scotland. With adequate resourcing, steps can be taken to ensure that a representative and directive sample of opinion can be recorded. In the absence of such resource and attention, there are risks of drawing presumptive, premature conclusions about what the Scottish publics will accept.

# 9 Recommended actions to develop a roadmap towards a $CO_2$ utilisation strategy for Scotland

The creation of a roadmap to develop a strategy for $CO_2$ utilisation in Scotland requires the preparation of a greater depth of evidence than this report was able to undertake. Many of the recommended actions therefore are aimed at commissioning further studies to provide this underpinning evidence in greater detail to allow policy options to be better understood. However, there are also some near term and cost effective steps that Scottish Enterprise could also consider to position Scotland as country interested in promoting the sector, and as a place open for business to technology developers to come and utilise Scotland's $CO_2$ resource.

**Recommended early actions to develop a roadmap towards a $CO_2$ utilisation strategy for Scotland:**

- Nominate a person or persons within Scottish Enterprise to be responsible for further investigation of $CO_2$ utilisation, and provide them with a dedicated budget to develop some of the actions listed below. They would be responsible for coordinating activities around the roadmap development, and in particular liaising with $CO_2$ utilisation stakeholders (including those from CCS, hydrogen and energy storage sectors). They would also be responsible for investigating Scottish, UK and European sources of funding for $CO_2$ utilisation *e.g.* under the sustainable chemicals demonstrator region.
- Identify in greater detail the type and tonnage of $CO_2$ resources in Scotland *e.g.* biogenic and non-biogenic sources. This action will provide additional data on $CO_2$ resources below the **10,000 tonnes per annum** reporting threshold of the Scottish Pollution Release Inventory. Collaborate with the CCS community who also have an interest in this data would be desirable. To encourage companies to report their $CO_2$ emissions, an independent analysis and verification of their $CO_2$ resource could be undertaken to give them further information on their resource; this detailed analysis and verification could be undertaken by an existing testing laboratory.
- Create and manage a database and map of the $CO_2$ resources identified through the previous action. The map and database could be centrally managed by Scottish Enterprise and $CO_2$ utilising companies would have a single point of contact to enable the identification of sources and locations of suitable supplies of $CO_2$. **Scotland could quickly position itself as a policy leader with this simple and cost effective project concept that provides a detailed database of its $CO_2$ resources.** Expanding a dialogue with the Scotch Whisky Association to provide a greater understanding of the carbon emissions from fermentation of its members would be an important step in understanding the potential CO2 resource from this sector.
- Use European and UK contacts to better understand the $CO_2$ utilisation opportunities presented by proposed revisions to European legislation and the impact of Brexit *e.g.* the EU Emissions Trading Scheme, the Fuel Quality Directive and the Renewable Energy Directive.
- Commission a market study to identify the type, tonnage, value and the geographical nature of the inorganic fertiliser demand within Scotland to establish the potential for import substitution with $CO_2$ derived fertiliser. This study should also include the type and sources of ammonia supply in Scotland. Existing reports into the Scottish production of fertilisers should feed into this.

- Commission a market study to identify the current scale of $CO_2$ demand and the potential future scale of $CO_2$ demand in Scotland (suppliers, source, volume, price and quality). It would be helpful to open discussions with the major Industrial Gas Manufacturers for this.
- Seek funding for an additional ClimateXChange fellow to work closely with the Scottish Government's Energy Team in order to create the necessary $CO_2$ utilisation technologies data to feed into the Scottish Electricity Dispatch Model. The fellow would undertake a detailed analysis of the potential economic and network benefits of various $CO_2$ deployment scenarios, and in particular an analysis of the opportunities to reduce curtailment.
- Commission a study to better understand the perception of various $CO_2$ products and processes from a range of Scottish publics. (it may be worthwhile expanding this under the banner of strategic carbon management to include CCS and $CO_2$-EOR too).
- Commission a study to better understand the legislative levers being considered within Europe to advance CO2 utilisation in particular or legislation that has an impact on the $CO_2$ utilisation sector. (it may be worthwhile expanding this under the banner of strategic carbon management to include CCS and $CO_2$-EOR too). This study should also consider which policy levers may be suitable at a Scottish level.
- Secure funding to co-fund industry to undertake initial $CO_2$ utilisation assessment studies.

As the evidence base is increased due to undertaking these early actions, then near-term actions would focus on the type of policies that would be helpful to attract and encourage companies to invest and grow in Scotland to take advantage of its $CO_2$ resource.

**Recommended near-term actions to develop a roadmap towards a $CO_2$ utilisation strategy for Scotland:**

- Facilitate a medium-term field study of the use of cellulosic carbonate fertilisers on microbial activity on a range of soils in Scotland, how this impacts the nitrogen use efficiency and release of $N_2O$ and how this impacts the retention of organic matter in soils under a range of differing conditions. This should have a particular focus on the soils typically used to grow spring barley for the Whisky industry.
- A demonstration scale $CO_2$ utilisation project competition should be promoted with Innovate UK and DECC to provide significant levels of investment to accelerate $CO_2$ utilisation in the food and drink and agricultural sector.
- Commission further research (with the CCS sector) to identify in greater detail the medium and long-term opportunities for Grangemouth in $CO_2$ utilisation including EOR, Industrial Biotechnology, low carbon manufacturing and as a hydrogen hub.

**Recommended actions to position Scotland as a place to come and develop and deploy $CO_2$ utilisation technologies.**

- Organise an annual $CO_2$ utilisation conference in combination with CCS, hydrogen and storage. The increasing synergy between these different areas suggests this will eventually happen. It is a simple and cost-effective way to position Scotland as being a policy leader in bringing these disparate communities together.
- Scottish Enterprise or the Scottish Government to join the Smart Specialisation Platform for carbon capture and utilisation: http://s3platform.jrc.ec.europa.eu/carbon-capture-and-utilization
- Investigate how Scotland could propose $CO_2$ utilisation through the Vanguard initiative, and through the Sustainable Chemicals Demonstrator programme.

# Technical Annex 1 – $CO_2$ utilisation academic capacity in Scotland

## Mapping of Scottish Academic expertise across sectors relating to Carbon Dioxide Utilisation – Executive summary[89]

This study was initiated to map Scottish Academic expertise across sectors relating to Carbon Dioxide Utilisation to inform future plans for Scotland. The purpose of this study was to identify the leading Scottish academic research underway in relevant areas.

For the purposes of this study, the relevant areas were defined in consultation with lead Partner University of Sheffield [Sheet 1, Appendix 2].

Scotland is home to the UK's largest Carbon Capture & Storage [CSS] research and development group, comprising a network of universities and institutions with experience and expertise across the full CCS chain. The partnership undertakes strategic research, often with industry partners, in the UK, Europe and further afield. With a little exploration, it is clear that there are additional underpinning scientific capabilities that flourish in the Scottish academic community. Relevant academic research was identified across twelve Scottish Higher Education institutions.

The study acknowledges that there are a considerable number of underpinning technologies and academic disciplines including chemistry, physics, policy, and engineering that directly or indirectly relate to Carbon Dioxide Utilisation as a whole. For example, mathematical modelling and computation underpin data analysis for the Informatics/Modelling sub-theme but it was considered beyond the scope of this study to map all the research groups relevant to computing in this report.

In addition to individual academic research groups, other key strengths in Scotland include the Industrial Biotechnology Innovation Centre and the Energy Technology Partnership research pool.

Research & technologies from a wide range of disciplines are relevant to *Carbon Dioxide Utilisation*. Other relevant and recent initiatives in Scotland include the business led Scottish Formulation Network and the Innovation Centres [Scottish Construction Innovation Centre, Industrial Biotechnology Innovation Centre, Data Lab and Centre for Sensor and Imaging Systems]

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[89] The full mapping report and spreadsheet are with Scottish Enterprise

# Technical Annex 2 - Linear and circular economy accounting and modelling using input-output methods

A key point to take from this is the distinction of a ***linear economy*** for wastes that accompany production and consumption activities (and are ultimately disposed) from the ***circular flow of economic resources*** that has been fundamental to economic thought since it was first proposed by Cantillon and Quésnay in the 18th Century. In the late 1960s, input-output accounting methods (originating with the Nobel Laureate, Wassily Leontief) formed the core tool in operationalizing the UN System of National Accounts aim of organising and relating all *economic* processes.

There has been extensive research activity on considering how input-output accounting methods and models can be developed to consider resource use and pollution issues. However, most work, such as studies using input-output methods for ***'carbon footprint'*** measurement, has tended to focus on carbon emissions purely as a by-product/pollutant consistent with the ***linear economy*** perspective. That is, as an economic 'bad' or by-product of the production/consumption of economic 'goods' to be disposed rather than potentially re-used. Basic environmental input-output methods involve specifying output-pollution (*e.g.* tonnes of $CO_2$ per £1million output) coefficients for each SIC-classified industry reported in input-output tables, as well as expenditure-pollution coefficients for households as final consumers (with the latter often distinguishing between emissions related to travel and non-travel activities). This type of approach is the one adopted by the Scottish Government in reporting carbon assessments of public budgets.[90]

However, there is a basis in the input-output literature for moving to more of ***a circular economy approach*** for a range of physical resources and pollutants. The University of Strathclyde team at the Centre for Energy Policy and Fraser of Allander Institute are currently working on developing a method to this end. The approach builds on seminal work by the afore-mentioned originator of economic input-output accounting, Wassily Leontief[91], which focused on the resource implications of internalising pollution externalities through the introduction of 'cleansing sector(s)' to the economic system. This work (examined and further developed for the case of physical waste by the team in Allan et al.[92]) does retain a linear economy approach, but with focus on the costs and distributional implications of disposing of waste products.

However, the current work at Strathclyde involves further developments that would facilitate consideration of how captured carbon (captured through activities sharing the characteristics of Leontief's 'cleansing sectors') may be utilised as inputs to some industrial sectors rather than simply being disposed. However, this approach also includes consideration of how 'disposal' may be reconsidered in terms of transportation and storage in a CCS context. The work is

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[90] http://www.gov.scot/Topics/Statistics/Browse/Economy/Input-Output/CarbonAssessment (online) accessed 2016

[91] Leontief, W. (1970), 'Environmental Repercussions and the Economic Structure: An Input-Output Approach', *The Review of Economics and Statistics*, Vol. 52 No. 3, pp. 262–271.

[92] Allan, G.J., Hanley, N.D., Mcgregor, P.G., Kim Swales, J. and Turner, K.R. (2007), 'Augmenting the input--output framework for common pool resources: operationalising the full Leontief environmental model', *Economic Systems Research*, Taylor & Francis, Vol. 19 No. 1, pp. 1–22.

currently supported through supervision by Karen Turner and Grant Allan of a PhD student, Elizabeth Briones (funded by the Mexican National Council for Science and Technology, CONACYT). The PhD project has particular focus on carbon capture in the power industry with utilisation potential via enhanced oil recovery activity (with ultimate off-shore storage). More general development of the methods may be a potential focus of the Scottish roadmap to a carbon utilisation strategy that results from the current project.

**Methods and data requirements for modelling $CO_2$ utilisation in a circular economy context**

The proposed approach would involve considering several steps and data/methodological issues:

**Basic environmental input-output accounting for industries that generate $CO_2$.**

The first issue in terms of data requirements is information of the physical amount of $CO_2$ generated in each Scottish industry per £1million output reported in the most recent in the series of annually produced Scottish input-output tables (currently 2012).[93] However, while Scotland is in an excellent position with regard to economic input-output accounting data, **a key problem is a lack of region-specific data on sectoral $CO_2$ emissions**. This is noted above as a key recommendation for action, the afore-mentioned carbon assessment of the Scottish budget uses information on $CO_2$ intensities for UK industries. The Scottish Government has only made one formal attempt at developing region-specific environmental input-output accounts for Scotland, reporting up to 2006.[94] Therefore, there would be a need to assess the extent to which region-specific data are required to effectively consider $CO_2$ utilisation issues, perhaps i**dentifying priority industries where $CO_2$ would be subject to utilisation opportunities**. **There would then need to discuss with Scottish Government the extent to which new data could be formally produced (and made publicly available) as opposed to constituting a new research requirement.**

**How many carbon capture and utilisation 'sub-sectors' in the Scottish case?**

In order to incorporate utilisation activity within an input-output based circular economy account we need to identify inputs and outputs for/from carbon capture (and possibly also the transport of $CO_2$) activity. The answer may be industry-specific (*i.e.* if different inputs are required to capture or utilise carbon in different industries). Moreover, where carbon is captured in one industry or location and utilised in another, there will also be a need to identify interactions with and input requirements of carbon transportation activity.

**Identifying input requirements and nature of 'output' delivery for new (potential) carbon capture (and possibly transport) 'sectors'**

Identifying input requirements will involve gathering basic information on and valuing (at basic or producer prices) different types of inputs required to conduct carbon capture activities - *e.g.* organic chemical amine. There is a need to distinguish between operational input requirements (part of the regular flow economic activity recorded in input-output accounts) from infrastructure requirements, where only the annual return to capital is part of the input-output

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[93] See http://www.gov.scot/Topics/Statistics/Browse/Economy/Input-Output/Downloads.

[94] See http://www.gov.scot/Topics/Statistics/Browse/Economy/SNAP/expstats/EnvironmentalAccounts.

flow of activity. Moreover, it will involve assessing the base level of domestic supply chain capacity in order to consider how much of the operating input requirements of capture activity could be met from the Scottish supply chain versus input requirements (with potential for simulation work to consider impacts of the evolution of activity). In terms of the corresponding output (noting that the value of input must equate to the value of output in any one industry or sector) the question of utilisation enters the picture. Where there is a demand for $CO_2$ as an input to industrial processes (*e.g.* as a feedstock in fuel, chemicals or polymers production processes) and this involves an implicit or actual ***transfer price***, we have a basis for valuing the new capture 'sectors' based on the value of their output as well as their input requirements. Where the value of output cannot compensate the value of input, the capture sub-sector must be balanced either through the gross operating surplus or a subsidy in the primary input portion of the input column for this sector.

- Where transport activity is involved to facilitate utilisation, we have the further issue of identifying operational input requirements as with capture, but with the captured $CO_2$ becoming an input (valued in an appropriate way as above). Again, there is a need to balance the total value of output 'sold' to utilising sectors (again with the absence of a compensating transfer price reflected through the gross operating surplus and/or a subsidy in the primary input sector of the new transport 'sector'.

**Adjusting input requirements of utilising sectors.**

There are three issues here. First, leading from the discussion above, there is the issue of how carbon 'inputs' are valued in utilising sectors. Second, it is necessary to identify how the input requirements/production technology of utilising sectors must be adjusted to reflect the change in production process. This in itself will involve two stages:

(i) identifying any existing input requirements that would change in the presence of $CO_2$ utilisation (*e.g.* enhanced oil recovery involving carbon flooding processes may be expected to be more labour and capital intensive than water flooding processes);

(ii) identifying and appropriately valuing in any additional inputs required to facilitate/support $CO_2$ utilisation (again separating capital/investment and operating input requirements and costs).

Third, there is again a need to balance inputs and outputs, which will again involve impacts on the utilising sectors' gross operating surplus and/or implicit or explicit subsidy requirement.

**General re-balancing of the input-output framework**

More generally, the steps presented above involve introducing new activities into the published Scottish input-output accounts, with adjustments to existing sectors (that supply inputs to capture, transport and/or utilising processes or use their outputs) as well as introduction of new potential or 'what if' sectors. It is advisable to try and re-balance at sectoral level wherever changes to existing or new activities are introduced as an overall re-balancing of the input-output accounts at the end of the process is likely to disrupt entries throughout the table.

As noted in the recommendations at the start of this section, **advice would have to be sought from the Scottish Government input-output team.**

**Scenario analyses**

Once a new ‘what if’ input-output account is developed there is a wide range of potentially useful scenario analyses that could be conducted to assess the implications of a move to a more circular economy. The most basic application may be simple multiplier analyses of potential ripple effects of new and adjusted activities. However, there would be interesting questions in terms of the impacts of the evolution of domestic supply chain activity to support carbon capture, transport and utilisation activity, of different support mechanisms, how the need for these may be reduced as scale economies are realised, and of how the evolution of carbon pricing impacts economic viability. However, as soon as we start to consider scenarios that may involve changes in prices, including but not limited to pressures of supply constraints, it would be advisable to consider embedding the input-output database in a more flexible computable general equilibrium (CGE) modelling framework.

# Appendix 1 - Understanding the Social Context of $CO_2$ utilisation in Scotland

**Publics**

There is no such thing as the general public, rather a heterogeneous mass of publics with diverse interests, concerns, aspirations and motivations. When introducing new industrial technologies, like $CO_2$ utilisation, what is of primary concern to one public (*e.g.* those living adjacent to a proposed site) may not resonate with other publics (*e.g.* those in communities further afield). Identifying which public or publics constitute your target population(s) and then moulding your communication and engagement strategy accordingly is essential to maximise the chance of securing favourable outcomes. One-size-fits-all strategies are often ineffective as they lack the appropriate tailoring.

Additionally, there are risks to assuming that general opinion data (*e.g.* secured via national polls) will translate directly into local project acceptance. While there can be correspondence, it is often rare that attitudes regarding a specified project will directly reflect the endorsement of a concept or technology considered in a more hypothetical sense. This apparent discrepancy is often noticeable within communities earmarked to host facilities; a phenomenon that has given rise to the term NIMBYism (Not in My Backyard). Crucially, however, research has begun to firmly question the utility, validity and applicability of this term. NIMBY is not only a pejorative term but one that makes a number of assumptions about the nature of local objection to so-called Locally Unwanted Land Uses (LULUs). For example, NIMBY assumes that people will endorse development of a LULU anywhere other than their backyard and that this local resistance is attributable to selfishness and / or ignorance; both these assumptions have been strongly contested by contemporary social scientific research.

While not ruling out NIMBYism as a part explanation for local opposition, social scientific research has yielded insight into the diversity of alternative reasons as to why communities might reject or accept industrial technologies. Broadly, three factors are important: (1) the attributes of the project; (2) the nature of the place in which it is proposed; and (3) the processes by which decisions are made.[95,96]

**Project Factors**

The anticipated risks and benefits of an industrial facility do affect whether or not it is embraced by a proposed host community. For instance, work into wind power shows that the perceived impacts on visual amenity and noise levels, and the effects on local heritage, wildlife and people's health and well-being are all often cited as reasons for objection of wind farms, alongside more self-interested concerns about depreciating house value.

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[95] Jones, C. R., & Eiser, J. R., 2009. 'Identifying predictors of attitudes towards local onshore wind development with reference to an English case study.' Energy policy, 37(11), 4604-4614.

[96] Devine-Wright, P., 2005. 'Beyond NIMBYism: towards an integrated framework for understanding public perceptions of wind energy.' Wind energy, 8(2), 125-139.

One should anticipate similarly diverse concerns shaping local perceptions of proposed $CO_2$ utilisation facilities. Indeed, formative public opinion research has already identified that people see a number of benefits (*e.g.* employment benefits) and risks (*e.g.* the risk of harmful gaseous and chemical emissions from $CO_2$ utilisation plant and associated $CO_2$ transportation and storage activities) associated with the technology at a general level.[97]

While public education about the risks and benefits of $CO_2$ utilisation will be important, it should not be assumed that such efforts will guarantee acceptance of projects (or indeed an acceptance of the principal *per se*). People form their opinions about new industrial technologies based upon a variety of things, including how the technology or context for its introduction are framed, as well as the perceived credibility and trustworthiness of the source of information.

Care will need to be taken to select trusted communicators and develop engagement strategies that recognise the varied antecedents of public attitudes towards $CO_2$ utilisation. For example, research indicates that public judgements of risk are often calculated on different dimensions to those of experts, incorporating considerations of risk familiarity and perceived morality.

This different way of calculating risk could have implications for the acceptability of $CO_2$ utilisation projects. Morally, for example, recent studies have indicated that some people question whether or not investment in $CO_2$ utilisation could encourage the continued use of Fossil Fuels or stifle and undermine a transition towards more sustainable lifestyles and business practices.[98]

**Appreciating more about the subjective factors likely to shape perceptions of risk relating to new industrial technologies, like $CO_2$ utilisation, is important to their successful promotion; as is the selection of trusted communicators to convey information about proposed projects and plans.**

**Place Factors**

**It pays to consider the historical and ongoing connections that publics share with their local environment when identifying locations for potential industrial facility development.**

If a proposal is seen to threaten a person's connections to a place, then this increases the chance that they will engage in oppositional behaviour; conversely, where a proposal is adjudged to enhance these psychological connections the greater the potential for active support.

The importance of place attachment and identity in shaping attitudes towards industrial facilities has been found in a number of studies relating to technologies such as tidal energy projects, offshore wind farms, CCS facilities and hydro-electric dams.[99] It should be expected that such considerations will shape emerging perceptions of $CO_2$ utilisation facilities. For example, it is reasonable to assume that where proposed $CO_2$ utilisation facilities are seen to

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[97] Jones, C. R., Radford, R. L., Armstrong, K., & Styring, P., 2014. 'What a waste! Assessing public perceptions of Carbon Dioxide Utilisation technology.' Journal of CO2 Utilization, 7, 51-54.

[98] Jones, C. R., Kaklamanou, D., Stuttard, W. M., Radford, R. L., & Burley, J., 2015. 'Investigating public perceptions of carbon dioxide utilisation (CDU) technology: a mixed methods study.' Faraday Discussions, 183, 327-347.

[99] Devine-Wright, P., 2009. 'Rethinking NIMBYism: The role of place attachment and place identity in explaining place-protective action.' Journal of Community & Applied Social Psychology, 19(6), 426-441.

augment or protect existing local industries (*e.g.* Chemical or Whisky manufacture) then one should encounter less local resistance to development.

There are relationships between place factors and the project factors outlined above, particularly in terms of risk familiarity. Constructing facilities on or close to existing industrial sites – where people are familiar with the risks of the neighbouring industry and / or derive a sense of identity or income from the facilities – could be anticipated to meet with lower resistance than new areas where people have not been exposed to such risk. This trend towards greater acceptance of proposals near existing development – so called YIMBYism (Yes in My Backyard) – while not guaranteed, has been observed in relation facilities like nuclear power plants.

There are, though, ethical considerations if opting for a policy of locating new facilities next to old. For instance, is it fair to impose new risks on those who are already burdened with existing risk from other facilities? Equally, is it fair to concentrate the economic benefits of new facilities in locations already profiting from existing plant?

**Process Factors**

The timing and extent of any public involvement in siting decisions is recognised as a key influencer of public opinion. Exclusive, decision-making processes, where choices are made, announced and then defended – so-called Decide-Announce-Defend (DAD) strategies – are often linked to higher levels of public dissatisfaction. By contrast, more participatory decision-making processes, which involve affected publics at an early stage and empower them to make substantive contributions to the choices being made, tend to be affiliated with a greater likelihood of satisfactory outcomes.[100]

While there are risks to involving communities in siting decisions (*e.g.* poorly conceived strategies of engagement can do more harm than good) and while there is no guarantee that such efforts will assure project success; there are also a number of benefits. For instance, meaningful involvement can help to yield a site-specific understanding of the public, project or place factors that are principally fuelling local opinion, as well as increasing trust in the process and its outcomes.

**In short, there is genuine potential value in involving affected publics in the decisions being made about new industrial technologies, particularly at a local level and if properly planned and resourced. There are, however, associated challenges in achieving this in a meaningful sense with new and unfamiliar technologies like $CO_2$ utilisation. One must think carefully about the practise of assessing people's opinions.**

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[100] http://static1.squarespace.com/static/53f5e2eae4b0593b948c9e4c/t/547f6e43e4b0c27762e5896e/1417637443121/feb09_engage_deliberate_decide.pdf

**Practise Factors**

Gauging public attitudes to new industrial technologies, like $CO_2$ utilisation, is not easy. Not only are there questions about who should be approached and the representativeness of responses received, but also about the reliability and validity of the registered opinions.[101]

Response rates to public surveys are typically low, with a bias towards those with particularly strong opinions. This raises the question of whether the opinions recorded via such methods are truly representative of a given public. Indeed, some research points to the emergence of 'democratic deficits' around facility siting, where an active oppositional minority hold disproportionate sway over planning decisions due their greater willingness to contribute to discussions.[102]

There are also questions over the quality of the opinions registered by simple surveys or polls. When assessing public perceptions of unfamiliar subjects, careful thought must be given to the manner in which opinions are assessed in order to reduce the potential for recording 'pseudo-opinions'. Pseudo-opinions are weak, misleading, changeable attitudes that are not particularly directive of behaviour. While it is rare that people providing such opinions are being deceptive, there are questions as to whether such opinions are reflective of those offered by a more informed audience.

Steps can be taken to enhance the quality of opinions expressed towards new and unfamiliar topics, including $CO_2$ utilisation. For example, by initially favouring more in-depth, deliberative forums for attitude assessment (*e.g.* focus groups, interviews, more in-depth surveys) – while not free of limitations – one can hope to register more informed opinions and informing opinions.[103]

**Considerations of practise are integral to successful assessment of a public's opinions. Poor practises produce poor data and poor data negatively affects the quality of decisions. Consideration should be given now to the formal assessment of emerging opinions to $CO_2$ utilisation in Scotland. With adequate resourcing, steps can be taken to ensure that a representative and directive sample of opinion can be recorded. In the absence of such resource and attention, there are risks of drawing presumptive, premature conclusions about what the Scottish publics will accept.**

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[101] Jones, C.R., 2014. 'Understanding and assessing public perceptions of Carbon Dioxide Utilization (CDU) technologies.' In P. Styring, A. Quadrelli, K. Armstrong (Eds.) Carbon Dioxide Utilization: Closing the carbon cycle (1st edition), Elsevier.

[102] Bell, D., Gray, T., Haggett, C., & Swaffield, J., 2013. 'Re-visiting the 'social gap': public opinion and relations of power in the local politics of wind energy.' Environmental Politics, 22(1), 115-135.

[103] de Best-Waldhober, M., Daamen, D., & Faaij, A., 2009. 'Informed and uninformed public opinions on CO 2 capture and storage technologies in the Netherlands.' International Journal of Greenhouse Gas Control, 3(3), 322-332.

# Appendix 2 – Tables of Scotland's fertiliser demand

*Table 7 - Fertiliser demand ('000 tonnes) in Scotland by type and by crop, calculated from tables EW3.1 and GB3.1 British Survey of Fertiliser Practice 2014*[104]

| | spring cereal | winter cereal | potatoes | sugar beet | oilseed rape | other tillage | all tillage | grass for grazing | grass for hay | grass for silage | grass not specified | all grass | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Ammonium Nitrate** | 45 | 47 | 1 | 0 | 9 | 1 | 97 | 47 | 2 | 21 | 0 | 53 | 165 |
| **Urea** | 7 | 8 | 0 | 0 | 4 | 0 | 19 | 7 | 0 | 4 | 0 | 9 | 31 |
| **Calcium Ammonium Nitrate (CAN)** | 2 | 0 | 0 | 0 | 1 | 0 | 1 | 2 | 0 | 0 | 0 | 1 | 5 |
| **Urea Ammonium Nitrate (UAN)** | 10 | 8 | 0 | 0 | 2 | 0 | 18 | 2 | 0 | 1 | 0 | 2 | 26 |
| **Other Straight N** | 3 | 6 | 1 | 0 | 1 | 0 | 12 | 1 | 0 | 0 | 0 | 0 | 14 |
| **Triple Superphosphate (TSP)** | 3 | 5 | 0 | 0 | 1 | 0 | 9 | 0 | 0 | 0 | 0 | 1 | 10 |
| **Other Straight P** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 |
| **Muriate of Potash (MOP)** | 3 | 7 | 1 | 0 | 1 | 0 | 13 | 1 | 0 | 3 | 0 | 5 | 16 |
| **Other Straight K** | 0 | 0 | 0 | 0 | 0 | 0 | 3 | 0 | 0 | 0 | 0 | 0 | 1 |
| **PK** | 7 | 16 | 0 | 0 | 0 | 0 | 22 | 5 | 0 | 2 | 0 | 5 | 32 |
| **NK** | 10 | 5 | 0 | 0 | 0 | 0 | 14 | 10 | 0 | 10 | 0 | 18 | 25 |
| **Low N (<19% N)** | 53 | 21 | 13 | 0 | 5 | 11 | 107 | 11 | 2 | 9 | 0 | 18 | 135 |
| **High N (>=19% N)** | 36 | 5 | 1 | 0 | 0 | 5 | 47 | 153 | 14 | 105 | 0 | 209 | 220 |
| **Other** | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 1 |
| **Total product ('000 tonnes)** | 178 | 128 | 19 | 0 | 24 | 17 | 360 | 240 | 19 | 156 | 0 | 323 | 682 |

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[104] ISBN 978-0-99297-350-6, https://www.gov.uk/government/collections/fertiliser-usage

*Table 8 - Fertiliser demand in Scotland by type and by month ('000 tonnes), calculated from tables EW3.3 and GB3.3, British Survey of Fertiliser Practice 2014*[105]

| | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Ammonium Nitrate** | 0 | 0 | 29 | 61 | 36 | 7 | 3 | 3 | 1 | 0 | 0 | 0 | 139 |
| **Urea** | 0 | 0 | 5 | 14 | 7 | 3 | 0 | 0 | 0 | 0 | 2 | 0 | 31 |
| **Calcium Ammonium Nitrate (CAN)** | 0 | 0 | 0 | 2 | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 4 |
| **Urea Ammonium Nitrate (UAN)** | 0 | 0 | 4 | 10 | 5 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 20 |
| **Other Straight N** | 0 | 2 | 10 | 10 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 23 |
| **Triple Superphosphate (TSP)** | 0 | 1 | 2 | 4 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 8 |
| **Other Straight P** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **Muriate of Potash (MOP)** | 0 | 2 | 5 | 5 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 14 |
| **Other Straight K** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 |
| **PK** | 0 | 0 | 10 | 3 | 1 | 0 | 0 | 1 | 4 | 3 | 0 | 0 | 23 |
| **NK** | 0 | 0 | 1 | 12 | 9 | 4 | 1 | 1 | 0 | 0 | 0 | 0 | 28 |
| **Low N (<19% N)** | 0 | 0 | 52 | 53 | 8 | 2 | 1 | 4 | 3 | 2 | 0 | 0 | 125 |
| **High N (>=19% N)** | 0 | 0 | 20 | 144 | 60 | 24 | 14 | 3 | 0 | 0 | 0 | 0 | 264 |
| **Other** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **Total product ('000 tonnes)** | 1 | 4 | 141 | 317 | 130 | 40 | 18 | 12 | 8 | 7 | 0 | 3 | 681 |

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[105] ISBN 978-0-99297-350-6, https://www.gov.uk/government/collections/fertiliser-usage

# Appendix 3 – Calculation of AGBarr's use of $CO_2$ for carbonating soft drinks

Calculation for AGBarr's use of $CO_2$ in Scotland using data from competition commission document on proposed merger of AGBarr and BRITVIC

https://assets.digital.cabinet-office.gov.uk/media/55194de0e5274a142b000488/130709_final_report.pdf

paragraph 2.9 pp9

*AG Barr is one of the leading soft drinks producers in the UK. It produced over 365million litres of soft drinks during its 2012 financial year (ending 28 January 2012).19 During its 2012 financial year, AG Barr generated total turnover (gross sales) of £223 million, of which 77 per cent was attributable to sales of carbonated drinks and 23 per cent to sales of still drinks.20 Approximately 55 per cent of its turnover was generated through sales in England, Wales and Northern Ireland and 43 per cent through sales in Scotland*

Therefore - assuming for Scottish plants

365 million litres of which 77% was to carbonated drinks and 43% of sales were in Scotland (and assumed to be manufactured in Scotland).

The amount of CO2 used to carbonate a litre of soft drink is taken as 5 grams per litre (http://www.fmf.uni-lj.si/~planinsic/articles/fizziology.pdf)

365 million litres in 2012 x 77% x 43% x 0.05g per litre = **604 tonnes** in Scotland in 2012

Even with a large margin for error in these calculations this is felt to be a limited area of demand in terms of the biogenic $CO_2$ resource in Scotland, estimated to be **0.5 million tonnes per annum** from distillery sector fermentation.

# Appendix 4 - Future potential for CCS in Scotland

The emerging CCS industry is currently in a state of flux. This is due to cancellation of the £1bn capital grant in 2015, which had been offered to UK CCS competition projects since 2007 and a lack of clear CCS strategy from the UK Government.

Within Scotland there is some on-going activity between industry and the Scottish Government to understand what is next for CCS in Scotland. The Scottish Government are taking a system view of decarbonisation, and are now looking beyond electricity to heating and transport as well[106].

The cancellation of the £1bn capital grant has meant that the Shell 'no longer see a future for the Peterhead project in the near term' [107] and with the uncertainty over future CCS strategy, commercial interest in CCS is reducing, which will likely lead to delays in future projects.

The cancellation of the capital grant, however, presents an opportunity for the Caledonia Clean Energy Project to become the CCS anchor project in Scotland, and link in with an industrial CCS solution for Grangemouth.

**The Energy Technologies Institute (ETI) have done extensive modelling of the UK energy system using their Energy System Modelling Environment (ESME), which shows that without CCS the UK economy faces doubling of the cost of carbon abatement from *circa* 1% to 2% of GDP to reach 2050 emissions reduction targets**[108].

The ETI put forward three scenarios for what the roll-out of CCS in the UK could look like up to 2030. Note these are not forecasts and predate the withdrawal of the £1bn capital grant.

A 2030 comparison of the three scenarios are summarised in Figure 20. The *concentrated scenario* focuses on build-out from the Phase 1 CCS projects; the *EOR-led scenario* uses a Wood Report[109] style push and market pull for significant $CO_2$ volumes to drive $CO_2$-EOR leading to coal being dominant; and the *balanced scenario* involves multiple regional clusters, fuels and capture technologies.

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[106] Presentation by Chris Stark, 2016. 'Policy Challenges for Low Carbon Energy'. SHFCA-CEP 'A New Roadmap for Low Carbon Targets' conference

[107] Shell spokesperson on implications of withdrawal of £1bn capital grant on Peterhead CCS Project: http://www.bbc.co.uk/news/uk-scotland-scotland-business-34357804 (online) accessed 2016

[108] ETI 'Carbon capture and storage: Building the UK carbon capture and storage sector by 2030 –Scenarios and actions' http://www.eti.co.uk/wp-content/uploads/2015/03/CCS-Building-the-UK-carbon-capture-and-storage-sector-by-2013.pdf (online) accessed 2016

[109] Sir Ian Wood, 2014. 'UKCS Maximising Recovery Review: Final Report' https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/471452/UKCS_Maximising_Recovery_Review_FINAL_72pp_locked.pdf (online) accessed 2016

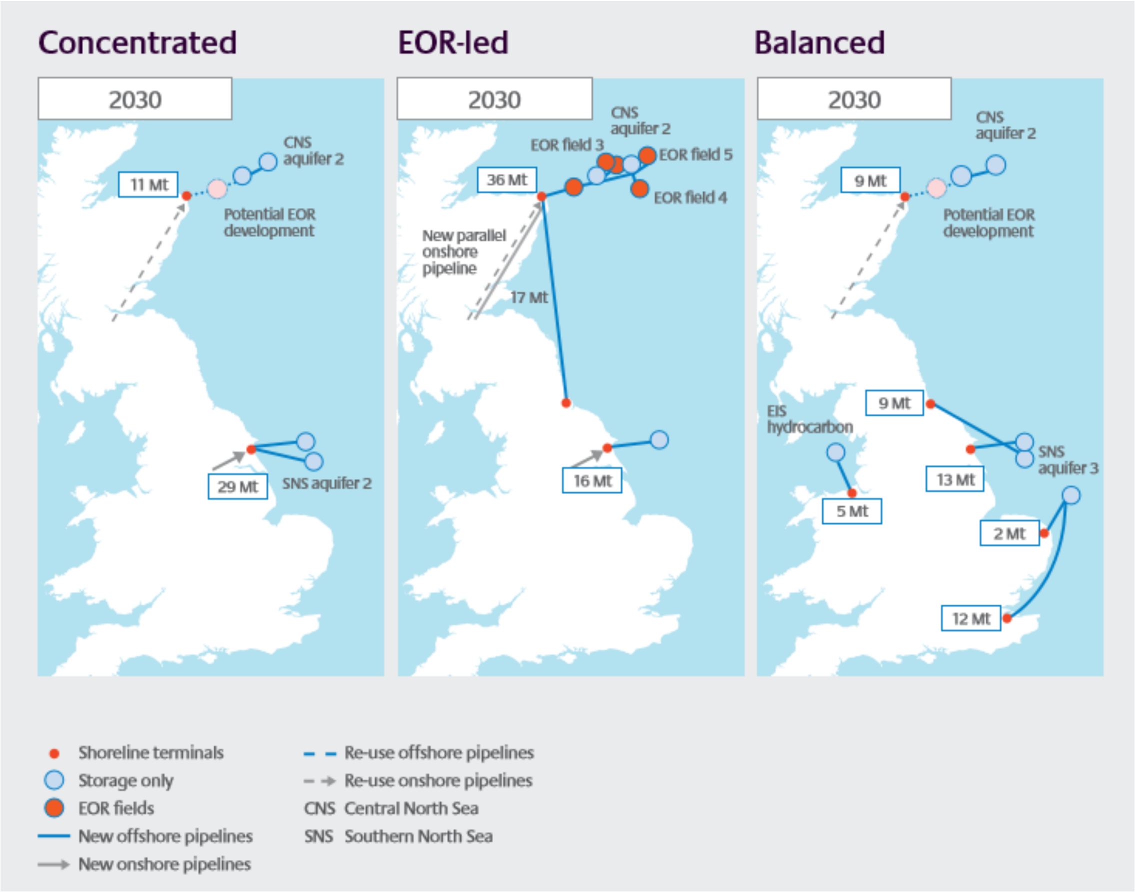

*Figure 20 – 2030 comparison of three CCS sector development scenarios for the UK*

Splitting out the Scottish and Grangemouth components of the three UK scenarios (Table 9), gives an idea of what the scale of a power and industrial CCS industry could look like. This can be helpful for comparing the volumes of $CO_2$ available from CCS to those required by $CO_2$ utilisation.

| Scenario | Region | $CO_2$ captured in million tonnes per annum | | | Example Power Stations with CCS for Scenario | Example Industrial CCS for Scenario |
|---|---|---|---|---|---|---|
| | | 2020 / 21 | 2025 | 2030 | | |
| **Concentrated (Scotland)** | Scotland | 0* | 5 | 11 | 2022 – Forth Coal CCS 1 Operational<br>2026 – Forth Gas CCS 1 Operational<br>2028 – Peterhead Gas CCS2 Operational | 2022 – Forth refinery & cement pilots<br>2027 – Forth Refinery 1 & Cement<br>2028 – Forth Chemical<br>2030 – Forth Refinery 2 |
| | Grangemouth only | 0 | 4 | 11 | 2022 – Forth Coal CCS 1 Operational<br>2026 – Forth Gas CCS 1 Operational | 2022 – Forth refinery & cement pilots<br>2027 – Forth Refinery 1 & Cement<br>2028 – Forth Chemical<br>2030 – Forth Refinery 2 |
| **EOR-led (Scotland)** | Scotland | 0* | 9 | 36 | 2022 – Forth Coal CCS 1 Operational<br>2026 – Forth Coal CCS 2 Operational<br>2029 – Forth Coal CCS 3 Operational<br>2030 – Scotland Coal CCS Operational | 2022 – Forth refinery & cement pilots<br>2027 – Forth Refinery 1 & Cement<br>2028 – Forth Chemical<br>2030 – Forth Refinery 2 |
| | Grangemouth only | 0 | 4 | 19 | 2022 – Forth Coal CCS 1 Operational<br>2026 – Forth Coal CCS 2 Operational<br>2029 – Forth Coal CCS 3 Operational | 2022 – Forth refinery & cement pilots<br>2027 – Forth Refinery 1 & Cement<br>2028 – Forth Chemical<br>2030 – Forth Refinery 2 |
| **Balanced (Scotland)** | Scotland | 0* | 5 | 9 | 2022 – Forth Coal CCS 1 Operational<br>2030 – Scotland Gas CCS Operational | 2022 – Forth refinery & cement pilots<br>2027 – Forth Refinery 1 & Cement<br>2028 – Forth Chemical<br>2030 – Forth Refinery 2 |
| | Grangemouth only | 0 | 4 | 9 | 2022 – Forth Coal CCS 1 Operational<br>2030 – Scotland Gas CCS Operational | 2022 – Forth refinery & cement pilots<br>2027 – Forth Refinery 1 & Cement<br>2028 – Forth Chemical<br>2030 – Forth Refinery 2 |

**NOTE: 1 million tonnes per annum removed due to uncertainty over future of Peterhead CCS project*

*Table 9 – Scotland and Grangemouth subset of the three CCS sector development scenarios for the UK*

*Element Energy and Pöyry, 2015. 'CCS Sector Development Scenarios in the UK' http://www.eti.co.uk/wp-content/uploads/2015/05/2015-04-30-ETI-CCS-sector-development-scenarios-Final-Report.pdf (online) accessed 2016*

The ETI lays out a series of key requirement to support development of the scenarios above. These are summarised in Table 10, with commentary around how they fit into the current CCS landscape.

| Key requirements underpinning ETI Scenarios | Comments |
|---|---|
| **Timely implementation of both CCS Commercialisation Programme projects** | Both projects unlikely to progress following withdrawal of £1bn capital grant |
| **Early investment in physical appraisal to expand the promising 5/42 and Captain aquifer stores and appraise further sites** | Early investment in physical appraisal challenging following loss of Phase 1 projects |
| **Enable early investment decisions by 'phase 2 projects' (the first tranche of projects which follow the Commercialisation Programme) by awarding a further 3 appropriately designed CfDs by 2020** | 'Phase 2 projects' challenged due to loss of Phase 1 projects |
| **Stimulate a robust project development pipeline by delivering clear signals to investors and project developers about the scale and strength of policy (levy control framework support) commitment to developing CCS** | Challenges with uncertainty around current UK Government CCS commitment and lack of clear strategy |

*Table 10 – Key requirements to support 2030 CCS scenarios*[110]

As summarised in Section 3, the current market for $CO_2$ across the UK is in the region of **2 million tonnes per annum** versus the potential to capture in excess of **8 million tonnes per annum** from across the Grangemouth Region.

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[110] Element Energy and Poyry, 2015. 'CCS Sector Development Scenarios in the UK' http://www.eti.co.uk/wp-content/uploads/2015/05/2015-04-30-ETI-CCS-sector-development-scenarios-Final-Report.pdf (online) accessed 2016

# Appendix 5 - Scotland's energy policy and energy transition: background and context

To achieve this, the Scottish Government has set out a range of targets for the energy system in which energy provision from renewable sources is intended to continue to play a significant and growing role. In 2010 'A Low Carbon Economic Strategy For Scotland' [111] was published which included the ambitions to decarbonise electricity generation by 2030, 'almost complete' decarbonisation of road transport and 'significant' decarbonisation of rail by 2050, and 'establish a comprehensive approach to ensure that carbon is fully factored into strategic and local decisions about rural and urban land use'. It is indicative of the growing and recent interest in $CO_2$ utilisation that it was not mentioned anywhere in this document published less than 6 years ago.

Subsequently the Scottish Government's Electricity Policy Generation Statement[112] published in 2013 stated that 'Scotland's generation mix should deliver: a secure source of electricity supply; at an affordable cost to consumers; which can be largely decarbonised by 2030; and which achieves the greatest possible economic benefit and competitive advantage for Scotland including opportunities for community ownership and community benefits'.

A number of interim targets exist to drive progress towards the meeting of these 2030 and 2050 objectives. These include the goal of providing the equivalence of 100% of Scottish electricity consumption from Scottish-sited renewable electricity facilities by 2020, as well as meeting 11% of heat demand and 10% of transport demand from renewable sources, alongside a reduction in energy consumption of 12% over the same period[113]. This range of targets sets Scotland overall as the most ambitious nation in the UK in terms of its existing greenhouse gas targets.

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[111] With a carbon intensity of 50gCO2/kWh by 2030 for electricity generation in Scotland (http://www.gov.scot/Resource/0042/00427293.pdf)

[112] Scottish Government (2013), *Electricity Generation Policy Statement*, http://www.gov.scot/Resource/0042/00427293.pdf

[113] Scottish Government (2016), *Energy in Scotland 2016*: http://www.gov.scot/Resource/0049/00494812.pdf

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