

# A Strategic European Research and Innovation Agenda for Smart CO<sub>2</sub> Transformation in Europe

## CO<sub>2</sub> as a resource

Enabling European industry to become more resource efficient, sustainable, and eco-competitive.



The Smart CO<sub>2</sub> Transformation (SCOT) project is a collaborative European project focussed on accelerating the market development of carbon dioxide utilisation; it is supported by funding from the European Seventh Framework programme. Carbon dioxide (CO<sub>2</sub>) utilisation is a broad term that covers a variety of innovative industrial processes that can transform carbon dioxide into a variety of value added products such as chemical products, synthetic fuels and buildings materials.

This is the SCOT project's **Strategic European Research and Innovation Agenda** document, designed to give the SCOT project's appraisal of where and how Europe should look to accelerate the market development of CO<sub>2</sub> utilisation processes and products.



Grant Agreement n° 319995  
[www.scotproject.org](http://www.scotproject.org)



### Dissemination level for Final Version

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PU	Public	
PP	Restricted to other programme participants (including the Commission Service)	
RE	Restricted to a group specified by the consortium (including the Commission Service) – initially restricted until final draft has been agreed – then it becomes PU public	
CO	Confidential, only for members of the consortium (including the Commission Service)	

### Document History

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Version	Final Version
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ISBN: 978-0-9572588-5-3 SCOT SERIA Paperback  
ISBN: 978-0-9572588-6-0 SCOT SERIA eBook-PDF

# GLOSSARY, ACRONYMS & ABBREVIATIONS

<b>Item</b>	<b>Description</b>
CCS	Carbon Capture and Storage
EU-ETS	European Emissions Trading Scheme
FQD	Fuel Quality Directive
GHG	Greenhouse Gas
ILUC	Indirect Land Use Change
JAP	Joint Action Plan
NOx	Oxides of nitrogen
PEM	Polymer electrolyte membrane
RED	Renewable Energy Directive
SCOT	The Smart CO <sub>2</sub> Transformation project
SERIA	Strategic European Research and Innovation Agenda
SOC	Solid Oxide Cell
SOx	Oxides of sulphur
TRL	Technology Readiness Level



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# Foreword

By 2050, Europe needs to have decoupled its economic growth from its emissions of carbon dioxide. This is a direct response to the compelling evidence from the increasing risks of climate change brought about by the anthropogenic emission of greenhouse gases, and carbon dioxide in particular.

Transitioning from industrial and energy systems that are primarily reliant on fossil fuels to non, or less carbon emitting energy sources is a broadly accepted policy choice of member states, although the exact technology choices and the speed of the transition vary. In addition to its low-carbon energy transition, Europe requires new approaches to secure and create domestic jobs and economic growth through innovation in technologies and the markets that they serve; carbon dioxide (CO<sub>2</sub>) utilisation is one of these innovative approaches.

Scientific and industrial progress has enabled us to imagine a future in which CO<sub>2</sub> becomes an increasingly important resource; a world in which we utilise CO<sub>2</sub> to create products. By accelerating development in the area of CO<sub>2</sub> utilisation, Europe can improve its industrial competitiveness whilst reducing its impact on the planet. However, for this to happen, there needs to be a clearer long-term strategy which itself depends on a stable long-term research and industrial policy framework. CO<sub>2</sub> utilisation also provides a route for Europe to realise its ambition to move to a circular economy. Support for the circular economy comes from a high level, as evidenced by First Vice-President Frans Timmermans statement on the 15th of July 2015:

*"Europe should be a frontrunner on the circular economy. I believe passionately in this because the future of the European economy is not in competing on low wages; the future of the European economy is not in competing on wasting finite resources. The future of the European economy is in the circular economy, in reusing, in putting things back into the economic cycle. This means rethinking the way we design, produce, consume and dispose of products."*

# What is CO<sub>2</sub> Utilisation?

CO<sub>2</sub> utilisation is a broad term that covers a variety of established and innovative industrial processes that utilise CO<sub>2</sub> as a source of carbon, by transforming it into value added products such as chemical feedstocks, synthetic fuels or building materials. CO<sub>2</sub> utilisation can therefore be viewed as a range of novel technology pathways that utilise CO<sub>2</sub>, by breaking the bonds between the carbon and oxygen atoms, and forming new bonds with other reactants. Most reactions will also require an additional energy input, which must come from low-carbon energy sources to prevent the emission of additional CO<sub>2</sub> elsewhere in the energy sector.

The SCOT project focuses on CO<sub>2</sub> transformation technologies and processes (Figure 1), and therefore other related technologies such as those for capturing and transporting CO<sub>2</sub> for carbon capture and sequestration (CCS) are not elaborated in detail. Direct physical uses of CO<sub>2</sub> without a transformative step are also outside the focus of the SCOT project e.g. enhanced oil recovery, using CO<sub>2</sub> as a solvent, or in carbonated drinks. However, CCS is nonetheless considered to be complementary rather than competitive in nature, and as such the SCOT project supports the continued development of this and other avenues for the direct use or sequestration of CO<sub>2</sub>. The SCOT project focuses on chemical transformations of the CO<sub>2</sub> molecule, therefore biological routes of transformation via for example microalgae are not elaborated upon.

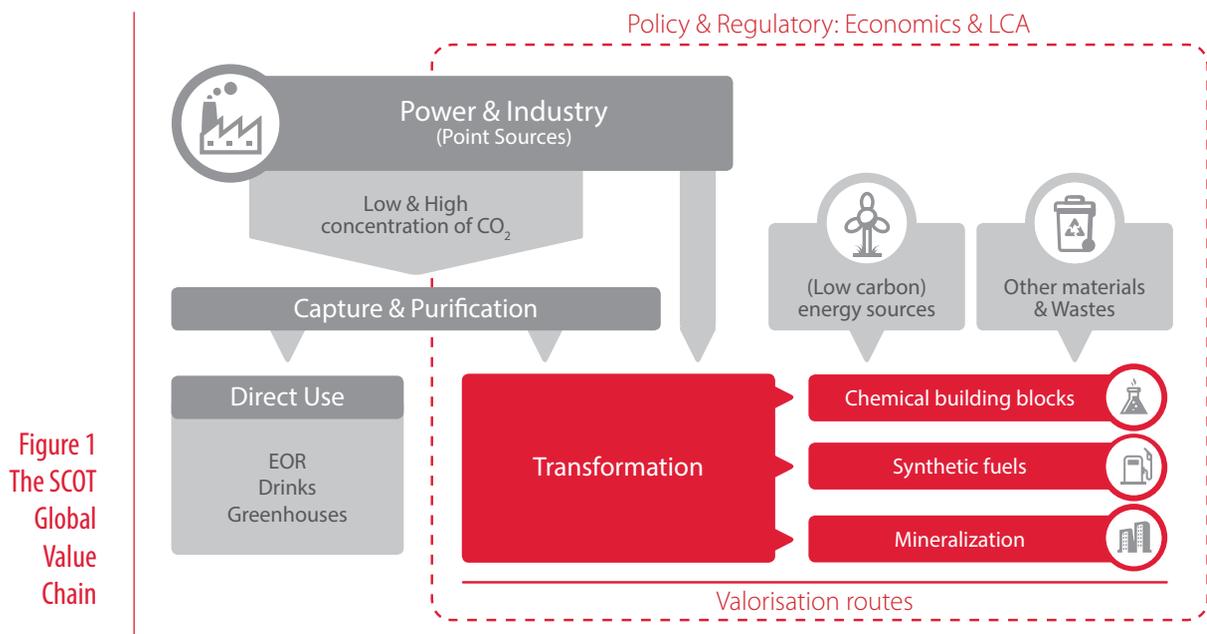


Figure 1  
The SCOT  
Global  
Value  
Chain

CO<sub>2</sub> can be transformed into a wide range of products from chemicals to fuels to building materials, from plastics to memory foams. The CO<sub>2</sub> is used as a carbon source replacing the carbon typically sourced from crude oil, natural gas or coal. Over 90% of organic chemicals are derived from fossil carbon and 5-10% of crude oil is used in the manufacture of these products; replacing this fossil carbon with carbon from CO<sub>2</sub> provides the opportunity for more sustainable process routes. Replacing fossil fuels themselves with synthetic fuels for other purposes, such

# What is CO<sub>2</sub> Utilisation?

as the storage of seasonal levels of energy would require market changes to allow synthetic fuels to share part of the market with conventional fossil fuels. Other advancing energy storage options such as batteries are modular, and could in theory be used to store seasonal amounts of energy, although the cost of these would be prohibitive for use interseasonally i.e. where the energy may only be charged or discharged once or twice a year. Nations have historically used fuels to store energy at scale to provide a security of supply, and the requirement of storing large amounts of energy over seasonal timeframes will still be a requirement in the future. Fuels, being an economic store of energy are therefore a logical choice, and lower carbon footprint synthetic fuels are a sensible approach for policy makers to consider.

Other inputs are also required to transform CO<sub>2</sub> into products. These inputs can be in the form of energy such as heat or electricity, or material inputs such as fly ash, hydrogen or epoxides. It is essential that any new CO<sub>2</sub> utilisation process has a lower carbon footprint over its total supply chain than equivalent products manufactured using fossil fuel routes. To achieve this, comprehensive Life Cycle Analysis (LCA) is required, which could also take into account avoided emissions.

Early in the SCOT project there was a feeling that there would be an inevitable market development of carbon capture technologies, due to the increased deployment of the nascent carbon capture and storage sector (CCS). This was thought to be of benefit to the CO<sub>2</sub> utilisation sector too, due to an increased availability of higher purity, low moisture CO<sub>2</sub> with low associated contaminants. Due to several policy announcements since 2013 regarding a reduction in the financial help to scale-up the carbon capture and storage sector, we feel the CCS sector will not necessarily develop at the necessary speed that would be helpful to the near-term development of Europe's CO<sub>2</sub> utilisation sector. It is therefore vitally important that there are continued efforts to develop carbon capture technologies that will help to decrease the costs of CO<sub>2</sub> as a feedstock.

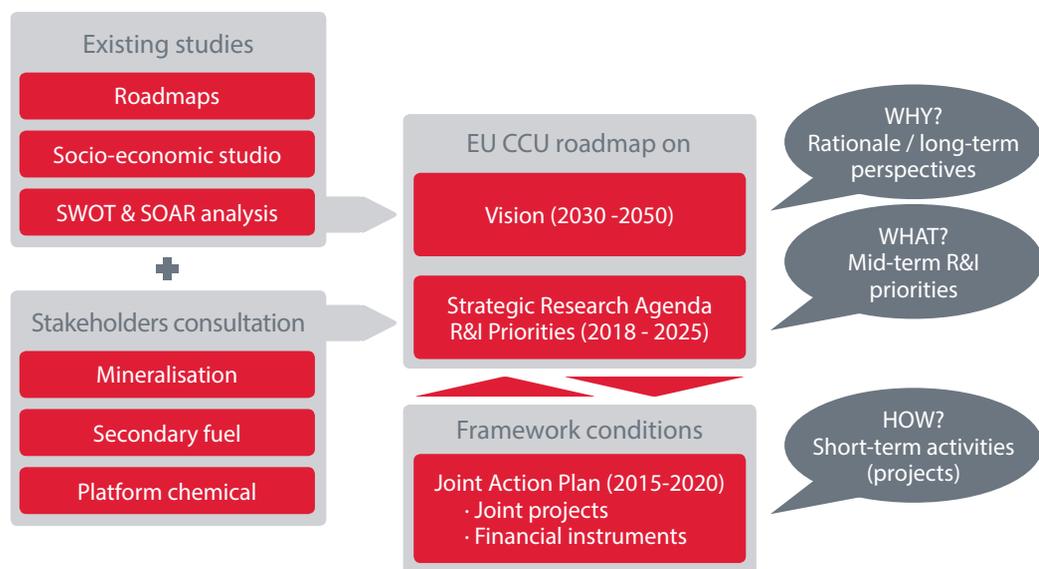
If there are mutual benefits to the CO<sub>2</sub> utilisation sector from the development of the CCS sector (and vice versa) it is also important to understand that there are major differences between the two sectors. A major difference lies in the CO<sub>2</sub> utilisation sector not being primarily focussed on carbon mitigation, but instead focussed on using CO<sub>2</sub> as a resource. Although there is likely to be a carbon mitigation effect, the size of this should be verified with transparent Life Cycle Analysis, which is especially important when one considers the use of avoided emissions. CCS in comparison is primarily focussed on carbon mitigation. Another main difference lies in the scale of the two areas, which itself is linked back to the focus on carbon mitigation. Over the medium term, CCS is viewed as needing to scale up to tens of millions of tonnes of CO<sub>2</sub> per annum to justify the cost of the infrastructure – the more CO<sub>2</sub> sequestered the better from a unit cost of infrastructure development point of view. Over the near term however, CO<sub>2</sub> utilisation is unlikely to reach this scale, as it will take time to develop and increase the markets for CO<sub>2</sub> utilisation products. Over the long-term, CO<sub>2</sub> utilisation products will have proven themselves to be a critical component in Europe's wider goals to drastically decouple its emissions from economic growth, and therefore the market for CO<sub>2</sub> utilisation products will be significant.

# Introduction

## AIM AND SCOPE

This document sets out a Strategic European Research and Innovation Agenda (SERIA) for CO<sub>2</sub> utilisation. The SERIA is influenced by the SCOT project's VISION document<sup>1</sup>, which was released in September 2015. Whereas the VISION document had a long-term focus describing the potential of the Sector by 2030, the SERIA gives more concrete guidance by outlining research and innovation priorities to achieve this Vision. The SERIA is complemented by the Joint Action Plan (JAP). The JAP defines the short to mid-term actions required to achieve the outcomes as described in the Vision and the research and innovation areas highlighted in this SERIA document.

Figure 2  
The key  
SCOT  
project  
deliverables



## METHODOLOGY

All project deliverables, including the SERIA, are the result of extensive discussion with the CO<sub>2</sub> utilisation community throughout Europe aimed at understanding the current state of CO<sub>2</sub> utilisation. During this research process the following activities have been conducted:

- **Over 300 interviews** with experts (industry, academia, policy makers) in CO<sub>2</sub> utilisation
- **Over 10 workshops** at (inter)regional level to synthesise and discuss preliminary results
- A **detailed regional assessment** to map CO<sub>2</sub> utilisation actors, the existing funds allocated to CO<sub>2</sub> recycling projects and to produce regional SWOT/SOAR analysis
- A more **comprehensive socio-economic analysis** to map major CO<sub>2</sub> emitters, energy infrastructures, and assess existing policy and regulations
- An **elaborate desk research** on three CO<sub>2</sub> transformation routes, mineralisation, power to fuels and chemical building blocks
- Extensive review of intermediate results by an international and renowned panel of experts and Public Consultation

<sup>1</sup> <http://www.scotproject.org/content/vision-smart-CO2-transformation-europe>

# Introduction

The successful development of CO<sub>2</sub> utilisation technologies is highly dependent on the way cross-cutting non-technical issues are tackled, as well as the technical advances. Acknowledging this, the SERIA document consists of three parts:

- 1. A non-technical part**, which is subdivided into a feasibility, policy frameworks, and societal uptake categories. The non-technical part of the SERIA identifies challenges stemming from each of these three categories.
- 2. A technical part**, which outlines a number of areas that would benefit from innovation out to 2030. However, one of the important areas that the community has strongly articulated is the need for continued (or increased) levels of fundamental research funding over this period, in order to provide the breakthroughs in fundamental science and engineering that are required to increase Europe's competitiveness over the long-term.
- 3. A specific CO<sub>2</sub>-derived products part**, that are believed to have the potential to reach commercialisation in Europe with supportive market frameworks in the near to mid-term future. Each CO<sub>2</sub>-derived product is described and specific research and innovation priorities are listed.

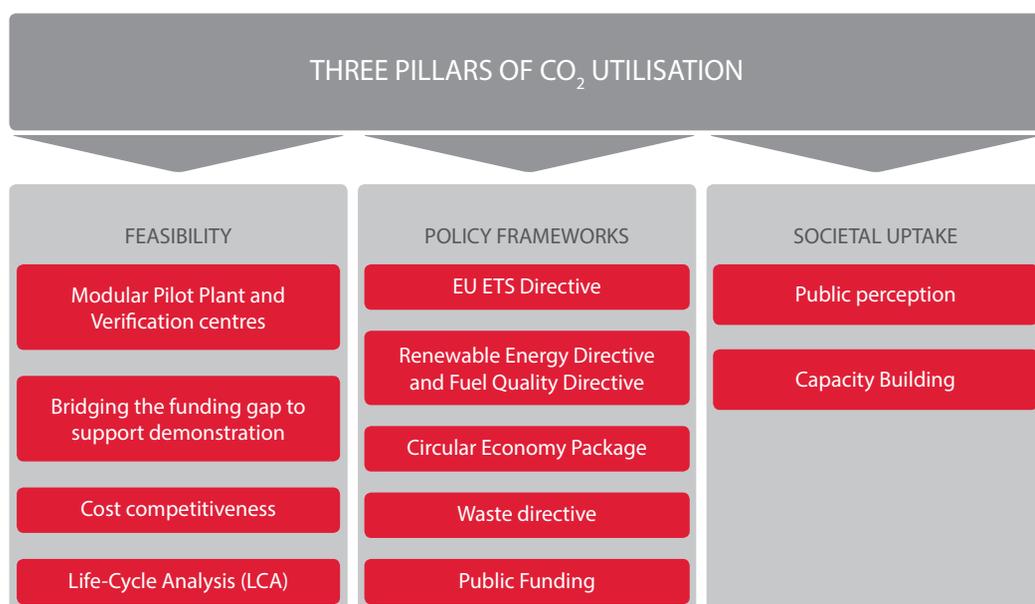
The document also includes an Appendix which covers areas of the CO<sub>2</sub> utilisation supply chain; low carbon energy, hydrogen production and the use of industrial wastes. These areas are not covered in detail and many have their own roadmaps and SERIAs, however discussions on CO<sub>2</sub> utilisation are not complete without the inclusion of these topics, as breakthroughs in these sectors will undoubtedly have a positive impact on the CO<sub>2</sub> utilisation sector too.



# 1 Non-technical challenges for CO<sub>2</sub> utilisation

The successful development of CO<sub>2</sub> utilisation technologies and their impact on Europe's transition to a more circular economy is not only of a technical nature, but is also highly dependent on the manner in which several cross-cutting, non-technical issues will be tackled too. These non-technical issues are interlinked and most often relate to the economic feasibility of CO<sub>2</sub> utilisation products in comparison to conventional fossil-fuel based products, policy frameworks, societal uptake, and the structure of intellectual property related activities in the sector. This section of the SERIA identifies challenges stemming from these categories and suggests some actions required to overcome these.

Figure 3  
Three non-technical pillars for CO<sub>2</sub> Utilisation sector emergence and their dependent variables.



**RECOMMENDATIONS**

- Establish Shared European Modular Pilot Plant and Verification Centres for CO<sub>2</sub> Utilisation to accelerate innovation and scale up through to the industrial deployment scale.
- Support longer term European and national funding pathways to enable progress from fundamental research to commercialisation.
- Promote the publication of Life Cycle Analysis of CO<sub>2</sub>-based processes.

The economic challenges of CO<sub>2</sub> utilisation can be great. Many CO<sub>2</sub> utilisation technologies are newly emerging and in common with other sectors looking to scale-up, they face a financial gap to advance successfully from lab through to market acceptance. Funding programmes enabling CO<sub>2</sub> utilisation technologies to reach higher Technology Readiness Levels (TRL) including commercialisation (TRL9) are an important economic lever for the acceleration of the sector by helping to **bridge this financial gap**.

**Need for Modular Pilot Plant and Verification centres**

The SCOT project has identified a need for Modular Pilot Plant facilities to accelerate CO<sub>2</sub> utilisation technologies through to commercialisation. A shared Modular Pilot Plant and Verification facility would allow industry and academia to book time to test various processes and technologies at a greater scale than possible in a research laboratory, and critically it would allow access to process gases from actual industrial sources rather than only synthetically created process gases. Such centres would benefit from the development of regional clusters that involve many relevant actors along the innovation chain including academia/universities, research centres, and industrial actors. If several of these centres are developed, then it is sensible to consider whether a degree of specialisation is warranted. This specialisation is likely to be dictated by the nature of local and regional co-funding to create these facilities, but a coordinated approach at a European level would also be desirable.

Shared Modular Pilot Plant and Verification Centres would help provide the additional knowledge and process optimisation required to translate a process through to a demonstrator level whilst limiting individual companies' financial risk, which has been identified as a key barrier.

**IDENTIFIED CHALLENGES**

- How can accelerated testing programmes be undertaken for CO<sub>2</sub> utilisation processes?
- How can the risk in TRL levels 3-6 be shared between public and private investment?
- Can public funding of shared European Pilot Plant and Verification centres help to reduce the scale-up financing needs of CO<sub>2</sub> utilisation technology developers?
- Can risks be reduced via a long-term European public funding commitment? How should this be implemented and what should it look like?
- How should CO<sub>2</sub> utilisation be incorporated into the SET plan and / or the ETS Innovation fund?

The Shared Modular Pilot Plant and Verification Centres would enable the process inputs such as flue gases, CO<sub>2</sub>, hydrogen, electricity and heat to be controlled in a precise and repeatable manner. Having access to actual flue-gas and by-product gas streams is thought to be a critical factor for the facility, but also having the flexibility to synthesise different flue-gas streams to allow a range of industrial plant outputs (CO<sub>2</sub> utilisation inputs) to be mimicked would be advantageous too. The industrial by-product gas streams containing CO<sub>2</sub> could be from the combustion of fossil fuels, the thermal decomposition of limestone or may be biogenic in nature from fermentation or combustion of biomass. The modular centres would allow technologies to be tested under a

range of dynamic and realistic conditions, which helps to drive innovation and also helps to de-risk various technologies by providing empirical data. Having better data would also allow more accurate techno-economic and life cycle analysis studies to be carried out. Technology verification is a critical part of the pathway to commercialisation, and the centres would allow technology developers to have their technologies undergo third party verification. Part of this would be in the form of accelerated testing, which is an important technique to accelerate technologies through to market acceptance. The centres would also create data that could feed into robust Life Cycle Analyses to satisfy potential reporting demands from legislation, or for the purposes of investment or indeed the eventual marketing of products to the end user. Eventually having a suite of predefined testing procedures, calculations and evaluations to drive standards and measurement protocols is desirable for a number of market and legislative reasons; the centres would help to formulate these.

Bringing more clarity to potential investors in areas of the techno-economics and verification are important steps in stimulating investments, and are seen as key areas that could help drive forward the wider adoption of CO<sub>2</sub> utilisation. In addition to the creation of data through testing programmes, the centres should also be able to provide an independent assessment of additional data used to evidence business plans, which would also be beneficial to the sector.

### **Bridging the funding gap to support demonstration**

Access to the right type of funding at the right time is essential for commercialisation of innovative processes. The funding gap from lab-scale through to demonstration scales is often associated with the “valley of death”, and presents a particular early stage financial challenge for companies. Funding challenges are not however limited to the early stages of development; later stages, closer to commercialisation are also likely to require increasing amounts of investments, mainly due to the increasing scale of the activity.

Long-term funding commitments from various public and private sources ensure a continuity of research programmes and are highly desirable situation for CO<sub>2</sub> utilisation at this time. Germany is a key example of this through the funding programme “Technologies for Sustainability and Climate Protection – Chemical Processes and Use of CO<sub>2</sub>”. This German programme has had three consecutive funding rounds to support 33 consortium projects which bring together science and industry to drive the development of innovative CO<sub>2</sub> technologies<sup>2</sup>.

In relation to existing programmes, collaborations should be formed that support CO<sub>2</sub> utilisation technologies in order to offer complementary solutions, such as:

The SET plan (>€70 billion) aims at accelerating the market uptake of low-carbon technologies, however, up to now, CO<sub>2</sub> utilisation has not been included as a targeted research activity. Currently CO<sub>2</sub> utilisation is perceived as an option to further improve the economic case of CCS (primarily from the perspective of enhanced oil recovery). The SCOT project believes that there are key differences between CO<sub>2</sub> utilisation and CCS, with CO<sub>2</sub> utilisation being considered as an independent but complementary sector. CCS is mainly focussed on larger point sources of CO<sub>2</sub> from the power and industrial sectors, CO<sub>2</sub> utilisation is appropriate for smaller point sources of CO<sub>2</sub>, especially those that are always likely to be remote from CCS infrastructure. CO<sub>2</sub> utilisation is therefore able to offer the re-use of CO<sub>2</sub> in many more places outside the context of the bulk capture systems normally envisaged with CCS. CO<sub>2</sub> utilisation also helps to achieve a number

<sup>2</sup> [https://www.bmbf.de/pub/technologies\\_for\\_sustainability\\_climate\\_protection.pdf](https://www.bmbf.de/pub/technologies_for_sustainability_climate_protection.pdf) (online) accessed 2/4/2016

of other broader initiatives such as the circular economy, sustainable chemical feedstocks and resource efficiency, it is not primarily concerned with emissions reduction.

The ETS NER400 Innovation Fund (successor of NER300) could be a useful tool in overcoming the scale-up challenge. It aims to support new-to-market low carbon innovations in energy intensive industry by reserving 400 million allowances (representing an estimated 5-10 billion EUR), from 2021 onwards. In addition, the unallocated allowances from the previous round (NER 300) could enable the early deployment of this fund. One of the major benefits of having access to a central fund of significant scale is to increase the coherence of the funding landscape, so that the funding is not scattered and overlapping, which can be the risk with uncoordinated smaller amounts of funding at a local or regional level.

### **Cost-competitiveness**

A major determinant of successful market entry of CO<sub>2</sub> utilisation products depends on their cost-competitiveness with existing products. Legislative drivers can help to create markets to allow scaling up to take place, with the expectation that this increased deployment will improve the cost competitiveness of the products in the medium term. Today, some innovative companies (e.g. Novomer, Carbon8, Covestro) have developed cost-competitive products that outperform existing approaches in certain properties. Others (e.g. Audi) have developed an innovative payment mechanism to allow their customers to buy their CO<sub>2</sub> derived fuels. Unfortunately, these successful examples are the exception rather than the rule. Nonetheless, these cases illustrate the fact that CO<sub>2</sub> utilisation technologies are, under certain circumstances, economically viable today. Looking ahead, techno-economic assessment studies of the most viable CO<sub>2</sub> utilisation routes are needed to support policy makers and businesses in their decision-making. This can be done through process simulation, cost modelling and sensitivity analysis on best currently available and proven technologies. This will help to establish the type of policy interventions that should be best suited to accelerate and enable the market uptake of CO<sub>2</sub> derived synthetic fuels, chemicals or construction materials.

### **IDENTIFIED CHALLENGES**

- What are the process steps that have a major impact on cost?
- How does the cost of inputs (e.g. hydrogen, CO<sub>2</sub>, energy etc.) impact the cost-competitiveness of particular CO<sub>2</sub> utilisation products?
- Can techno-economic analyses be performed to identify potential products and production routes that are likely to be the most economical in differing geographical situations?
- What are the location and types of available CO<sub>2</sub> resources?

The nature of plant economics and layout may fundamentally change, as the historical paradigm of scaling up steady state processes to take advantage of economies of scale (for process inputs as well as the plant equipment itself) is complemented by a more modular approach. Process design always involves a trade-off between several competing aims, and it is possible that the flexibility of a plant would become more important as a design driver in the future. Process economics may therefore be more dependent in the future on the flexibility of a system, rather than focussing predominantly on achieving higher efficiencies through economies of scale and steady state operation. The driver for flexibility is due to the increased frequency of lower-cost electricity, which itself is an outcome of the continued expansion of weather dependent renewable generation in many member states. This is a preferred policy option to reduce the amount of emissions from the power sector. However, the timing, frequency and price of future electrical energy in various markets is highly challenging to

predict, and this clearly has a major impact on the process economics in terms of the balance between CAPEX and OPEX due to the number of hours in a year that the lower cost electricity may be available.

The current production of sustainable synthetic fuels of non-biological origin are largely uncompetitive in comparison to fossil fuels at this time. Access to sources of low cost non-fossil hydrogen are of particular importance from a CO<sub>2</sub> utilisation perspective<sup>3</sup>. Policy makers should give due consideration to the creation and increase of markets for CO<sub>2</sub> derived fuels, as it is only through the increase of deployment that learning rates are able to impact on cost reductions through scaling up production. Due to the scale and volume of fossil fuel markets, even a small percentage of these markets dedicated to synthetic fuels of non-biological origin would have a significant market pull through.

In the case of using CO<sub>2</sub> for mineralisation, some technologies have been demonstrated at pilot plant scale level (TRL 6-8), and have been deployed in niche commercial applications<sup>4</sup> (TRL 9) such as the treatment of waste (Waste-to-Disposal and Waste-to-Product) or to accelerate the curing time of cementitious products that use Portland cement. In many cases, the cost of CO<sub>2</sub> purchased from firms that supply CO<sub>2</sub> is the limiting factor in the amount of CO<sub>2</sub> actually utilised in these processes, rather than the amount of CO<sub>2</sub> that could be utilised. Due to the lower value to weight ratio of mineralised products (in comparison to other CO<sub>2</sub> utilisation products) the proximity of the production process to various feedstocks and markets is typically a major factor in controlling transport costs, and therefore the cost of the product.

Finally, when constructing industrial plants (e.g. for biogas production), industrial symbiosis should be considered to allow CO<sub>2</sub> resources to be more readily utilised. There is an economic driver here, to reduce the costs of transportation of CO<sub>2</sub>, and an increase in knowledge of current available sources of CO<sub>2</sub> would be of benefit. Having a central database of sources and types of CO<sub>2</sub> would be a helpful asset at a member state or regional level, especially if it covered emitters that are lower than the minimum 10000 tonnes per annum threshold for reporting to the European Pollutant Release and Transfer Register<sup>5</sup>. A benefit of creating the database would also be to highlight those companies with a potential CO<sub>2</sub> resource that are actually interested in making it available to the CO<sub>2</sub> utilisation sector, as not all emitters will wish to. This would help companies seeking sources of CO<sub>2</sub> to make contact with companies that they wish to find a market for their CO<sub>2</sub>. This might suggest that the database would initially be better implemented by being voluntary. This type of database and data would provide a greater level of understanding of the European CO<sub>2</sub> resource, and would be helped by the commissioning of CO<sub>2</sub> utilisation assessments at a member state or regional level.

### Life Cycle Analysis (LCA)

In order to design environmentally sound processes and create greater awareness about the benefits that CO<sub>2</sub> utilisation products and processes can deliver, a stronger evidence base concerning the environmental impacts of CO<sub>2</sub> utilisation is essential. Life Cycle analysis increases the understanding of the positive and negative environmental impacts that technologies can have, and is key to decision making regarding the environmental sustainability of a process.

3 A variety of technologies can be considered for hydrogen production; many use electricity such as alkaline, polymer electrolyte membrane (PEM) and high-temperature water electrolysis, sodium chloride electrolysis and hydrocarbon arc furnace while in other cases, hydrogen is produced as a by-product (such as manufacturing of chemicals like chlorine).

4 [www.c8a.co.uk](http://www.c8a.co.uk) (online) accessed 2/4/2016

5 <http://prtr.ec.europa.eu/> (online) accessed 2/4/2016

Life Cycle Analysis can be an effective tool to enable the comparison of different processes and process routes. It enables an examination of the system-wide effects (cradle to grave, well-to-wheel, etc.) of particular processes, taking into account the different inputs and outputs (air, water, waste, energy etc.). In theory this should allow processes to be comparable, in reality however, it is highly dependent on agreement between the practitioners of LCA to use harmonised functional units and boundaries in order to provide a high degree of comparability. Therefore, for an LCA to be most beneficial, a common guidance framework for CO<sub>2</sub> utilisation LCA is highly desirable to inform better decision-making, and compare different processes on a similar basis (benchmarking). As a tool to develop an evidence base, LCA should allow policy makers to determine which CO<sub>2</sub> utilisation routes are better suited to various policy priorities e.g. the sustainability of feedstocks to the chemical sector.

### IDENTIFIED CHALLENGES

- Can a common framework for LCA in the sector be established?
- Can an increase in the amount of open-source data on the LCA of the different CO<sub>2</sub>-derived products be encouraged?

Currently there is a lack of published data on the LCA of different CO<sub>2</sub> derived products and processes and for policy to be more evidence based, products need to be benchmarked against each other. For instance, in markets that continue to need the energy density of liquid fuels, power-to-liquid CO<sub>2</sub>-derived fuels should be compared to other types of liquid fuels. In mineralisation, materials that utilise CO<sub>2</sub> should be compared to equivalent building materials. Each product has a certain range of environmental impacts, which can be compared to equivalent products using an LCA methodology. Lack of publicly available data on the properties and environmental impacts of products and processes makes benchmarking a resource and time intensive exercise with large uncertainties.

In order to deal with this lack of published data, the SCOT project proposes two recommendations:

1. A more consistent LCA methodology for CO<sub>2</sub> utilisation which expands upon ISO 14040/14044 should be promoted. The framework guidelines should encourage comparable system boundaries and give guidance on how to select an appropriate functional unit, benchmark processes and allocate environmental impacts. These should be clearly defined to enable a greater level of analysis and understanding. Also a key element to allow repeatable LCA is high transparency regarding uncertainty of data and subjective weighting of different elements.
2. The lack of published data should be addressed by having future public R+D investments in pilot plants incorporate clauses that increase the amount of detail and data for LCA calculations that are published. This would be of benefit to the wider community and policy makers. However, this is a complex area that needs to carefully balance the requirements to protect commercially sensitive information too.

RECOMMENDATIONS

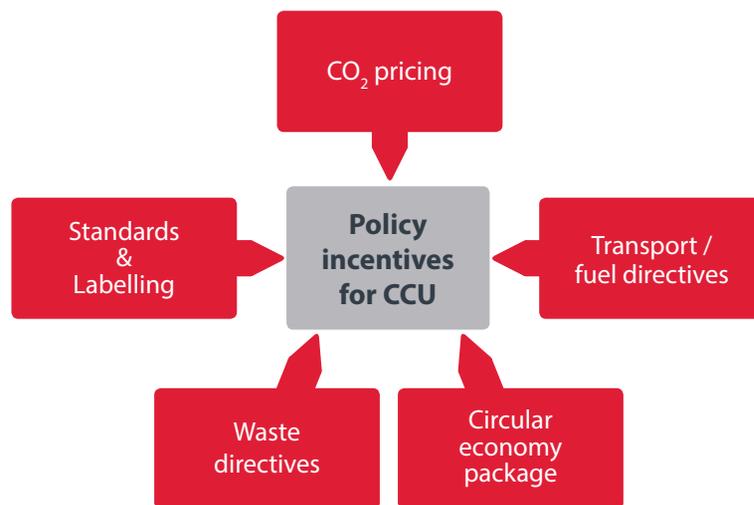
- Analysis of the impact of proposed legislation on the CO<sub>2</sub> utilisation sector.
- Provide greater clarity with respect to CO<sub>2</sub> and the circular economy and waste directive legislation.

CO<sub>2</sub> utilisation processes hold the potential to decouple economic growth from carbon emissions and support Member States’ resource efficiency agendas. However, due to the early stage nature of the CO<sub>2</sub> utilisation sector, many European policies have been written with little or no regard to the utilisation of CO<sub>2</sub><sup>6</sup>. The potential interplay of legislation can be confusing, and the impact of regulations on the market development of the CO<sub>2</sub> utilisation sector is still not well understood. Also, the direction that existing instruments should evolve to stimulate development of the sector is relatively unknown. Analysis of Europe’s existing policy instruments should continue, in order to provide greater clarity and understanding of their impact on the CO<sub>2</sub> utilisation sector. It is highly desirable for the CO<sub>2</sub> utilisation sector to be considered when the impacts of legislative changes are being analysed and developed.

As CO<sub>2</sub> utilisation is not currently cost competitive in several areas, there is likely to be a powerful legislative role for policy makers to encourage a greater uptake of CO<sub>2</sub> utilisation in certain markets to allow costs to improve through deployment at scale, e.g. CO<sub>2</sub> derived fuels and CO<sub>2</sub> derived chemical feedstocks.

Some policy areas that impact the business case of CO<sub>2</sub> utilisation processes are detailed in Figure 4

Figure 4  
EU policy  
instruments  
and directives  
impacting  
on the  
development of  
CO<sub>2</sub> Utilisation  
in Europe



**EU-ETS Directive**

The EU-ETS (European Union’s Emission Trading System) puts a price for industry on the right to emit CO<sub>2</sub>. Today, the utilisation of CO<sub>2</sub> is not included in the ETS as CO<sub>2</sub> utilisation is not considered a ‘permanent store’ of the CO<sub>2</sub> under the legislation. This can be traced back in the so-called Monitor and Reporting Guidelines regulation, which specifies that the transfer of inherent or pure CO<sub>2</sub> shall only be allowed for the purposes of long-term geological storage i.e. CCS. This implies that the utilisation of process CO<sub>2</sub> streams is not able to be considered under the ETS, and that industries that reuse carbon as a resource may be faced with a potential

<sup>6</sup> EU ETS Directive, Renewable Energy Directive, Fuel Quality Directive, Circular Economy Package, ETS innovation funds, Important Projects of Common European Interest, SET Plan, Industrial Emissions Directive

economic penalty, as they would still be obliged to surrender emissions allowances for the CO<sub>2</sub> that was utilised.

## IDENTIFIED CHALLENGES

- Can certain types of mineralisation be included in the ETS alongside CCS?
- What do “avoided emissions”, “low carbon technologies” and “sufficient scale” mean under the ETS amendment proposal? What is in and out of scope?

The legislative proposal for the EU ETS<sup>7</sup>, released in July 2015, appears to open the potential to incorporate CO<sub>2</sub> utilisation under the ETS. This supports the overall aim of the proposal, which is to drive forward innovation and reduce emissions<sup>8</sup>. The proposal states that:

- ‘allowances will not need to be surrendered for CO<sub>2</sub> emissions which are permanently stored or avoided’ (whereas previously only emissions that were permanently stored were eligible)
- ‘breakthrough innovation in low-carbon technologies and processes’ (are now being considered to be eligible for the ETS Innovation Fund).
- ‘EU ETS allowances should be used to provide guaranteed rewards or deployment of CCS facilities, new renewable energy technologies and industrial innovation in low-carbon technologies and processes in the Union for CO<sub>2</sub> stored or avoided on a sufficient scale.’

Assuming the amendments are incorporated into the legislation, there is a need to clarify what is in scope. How CO<sub>2</sub> utilisation products or processes relate to “breakthrough innovation in low-carbon technologies and processes”, “avoided emissions” and “sufficient scale” is not known. For example, would sufficient scale imply that only CCS and CO<sub>2</sub>-EOR are eligible but a mineralisation route at less than 5000 tonnes per annum might not?

A key criterion that the ETS must take account of is whether a potential CO<sub>2</sub> pathway results in a net reduction of CO<sub>2</sub> emissions to the atmosphere in comparison to alternative routes. The analysis of avoided emissions under the ETS will undoubtedly be a complex area which requires the transparency and sharing of data recommended in the LCA section of the previous section<sup>9</sup>. CO<sub>2</sub> utilisation can provide a degree of carbon management by using CO<sub>2</sub> as a feedstock that retains the carbon within a product. However, depending on the product, the carbon is then either retained permanently e.g. in a mineralised waste or temporarily e.g. in a CO<sub>2</sub> derived fuel. The end-of-life of the product also has a bearing on any potential mitigation effect. For example, if the product’s end-of-life release of carbon to the atmosphere is interrupted by a carbon capture plant, then the carbon molecule has the opportunity to be reused again and possibly again and again.

Apart from the direct uptake of CO<sub>2</sub>, by transforming CO<sub>2</sub> into products, CO<sub>2</sub> utilisation can also lead to avoided emissions by displacing fossil-based feedstocks that would otherwise have been used. In this way the carbon that is utilised from CO<sub>2</sub> can substitute for the carbon from a fossil product.

Legislation could reward certain CO<sub>2</sub> utilisation processes that store CO<sub>2</sub> permanently in a similar manner to CCS. If the lifetime of CO<sub>2</sub> storage within mineral carbonation products is similar to that of geological storage, it should be incentivised equally under the ETS. However,

<sup>7</sup> COM (2015) 337 - Proposal amending Directive 200387EC to enhance cost-effective emission reductions and low carbon investments

<sup>8</sup> EP Event, 2016, Re-plumbing the EU ETS: low-carbon innovation and carbon leakage in a post-Paris world

<sup>9</sup> Elaborated in the SCOT EU ETS policy briefing paper.

the incentivisation of CO<sub>2</sub> utilisation products with short lifetimes such as fuels should **not** be rewarded under the EU-ETS through 'avoided' emissions. Firstly, the EU-ETS has been set-up with the aim of reducing emissions from industrial installations themselves, rather than their end-products. Secondly, it is extremely challenging to define a measure to reward avoided emissions in individual industrial processes transparently and fairly. This is in part due to the variation in the choice of benchmark processes that could be chosen to compare with the CO<sub>2</sub> utilisation process itself. Taking these two reasons into account, rewarding CO<sub>2</sub> utilisation products through an 'avoided' emissions route could negatively affect the credibility of the ETS at this time. The EU-ETS amendment may therefore seem to enter a grey area that potentially impacts on legislation that is already in place to promote products which have a lower carbon footprint (e.g. Renewable Energy Directive, Fuel Quality Directive).

### **Renewable Energy Directive and Fuel Quality Directive**

CO<sub>2</sub>-derived fuels, synthesised using renewable energy, offer an alternative to producing biofuels from crops or the use of fossil fuels. They can help to make the European transport sector more sustainable through the use of fuels with lower lifetime emissions, and provide a method of reducing Europe's import dependency of fossil fuels too. Additionally, CO<sub>2</sub> derived fuels can offer an energy storage medium for renewable energy that is scalable, which is likely to take on more importance with the increasing deployment of weather dependent renewable energy generation. Most CO<sub>2</sub> derived fuels are not competitive with fossil fuels at this time (a similar case to biofuels), so legislative action to create a market driver will be required to increase the deployment in this part of the CO<sub>2</sub> utilisation sector.

#### **IDENTIFIED CHALLENGES**

- How can market pull through be stimulated for CO<sub>2</sub> derived fuels?
- To what extent should the fuel blend of a CO<sub>2</sub> derived fuel be increased e.g. methanol?

The European Parliament made an important step towards recognizing the benefits of CO<sub>2</sub>-derived fuels by passing the Directive to reduce indirect land use change for biofuels and bio liquids, the so-called "ILUC Directive". The amendment has had an effect on the Renewable Energy Directive (2009/28; RED) and the Fuel Quality Directive (2009/30; FQD), the two main policy levers by which the business case of CO<sub>2</sub>-derived fuels are affected. The RED mandates that by 2020 at least 10% of EU transport fuels come from renewable sources. The FQD defines the renewable content of fuels and covers many facets of fuel production.

The 'ILUC' Directive puts in place extra incentives for the use of CO<sub>2</sub> as a feedstock for transport fuels as advanced renewable fuels are counted double towards the 2020 target of 10% for renewable energy use target in transport, giving it a higher market value. In addition, the Directive sets an indicative 0.5% sub-target for advanced renewable transport fuels as a reference for national targets. This quota should be adopted by Member States on a voluntary basis in 2017.

Another issue is that although the recent 'ILUC' Directive has introduced CO<sub>2</sub> derived fuels, it has not provided limits regarding the life cycle analysis of these fuels. In fact, the Directive empowers the Commission to adopt a delegated act before December 2017 establishing the GHG default values for carbon dioxide fuels with which they will count toward CO<sub>2</sub> reduction goal set out in the FQD.

Having a number of different routes to provide non-fossil liquid hydrocarbon fuels is helpful for the European transport system which will still require liquid hydrocarbon fuels in some

transport areas even over the long-term e.g. the aviation sector. Legislation should therefore encourage the development of these different routes by encouraging a market pull through via different hydrocarbon routes i.e. through both biological and non-biological routes.

### **Circular Economy Package**

The Circular Economy Package is designed to stimulate Europe's transition towards a circular economy which will boost Europe's competitiveness, foster sustainable economic growth and generate new jobs.

In the current text of the circular economy communication "Closing the loop - An EU action plan for the Circular Economy"<sup>10</sup> the reuse of CO<sub>2</sub> is mentioned as a footnote under gaseous effluent reuse within the context of industrial symbiosis.

### **IDENTIFIED CHALLENGES**

- How could CO<sub>2</sub> utilisation be better integrated in the Circular Economy Package?

The current text has a focus on non-gaseous flows, which requires specific clarification for the reuse of CO<sub>2</sub> as a gaseous effluent by-product. Without clarification, there is a chance that this may hamper the development of CO<sub>2</sub> utilisation but also hamper the development of other industrial gaseous effluents too. Especially for a more circular chemical industry the inclusion of gaseous effluents is a prerequisite for a broader and more sustainable circular future.

It is important therefore to determine how CO<sub>2</sub> feedstocks can be incorporated in the package to deliver benefits and avoid confusion.

### **Waste Directive**

Directive 2008/98/EC (The Waste Framework Directive), provides the general legal framework of waste management requirements for EU member states and sets out the basis for waste management definitions. Waste management is a key element of the circular economy package, and better development of supply chains for waste management is required to lead to a higher recycling rate; therefore, improving the environmental footprint of materials flowing through the economy. CO<sub>2</sub> utilisation could make a significant impact in the area of waste mineralisation to produce materials able to be used in the construction sector.

It is the view of the SCOT project that CO<sub>2</sub> emissions should remain legally classified as a not being a 'waste'. However, CO<sub>2</sub> does have a role to play in the remediation of other waste streams through mineralisation.

### **IDENTIFIED CHALLENGES**

- Can CO<sub>2</sub> utilisation techniques in be included in waste remediation legislation?
- Do the 'by products' or end of waste criteria in Waste Frameworks Directive need revised to better encourage CO<sub>2</sub> utilisation?
- How can certain CO<sub>2</sub> utilisation processes be included as a Best Available Techniques (BAT)?
- Can end-of-life criteria be harmonised across Member States to allow the development of a single market?

<sup>10</sup> <http://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1453384154337&uri=CELEX:52015DC0614>

CO<sub>2</sub> utilisation mineralisation technologies have the ability to support the European ambition to avoid the landfill of some wastes, and offer techniques that improve the production processes of some industries. CO<sub>2</sub> mineralisation provides an opportunity to phase out completely the landfilling of some types of solid wastes (steel sector fines, bauxite, quarry fines, wood and paper ashes or metal dust) and stabilising their potentially hazardous elements. Wastes from steel production, for instance, can be treated with CO<sub>2</sub> to produce marketable products promoting process circularity and enhancing waste management (e.g. Recoval in Belgium and Carbon8 in the UK). Therefore, these types of techniques should be included among the Best Available Techniques reference documents providing alternatives to landfilling.

### Public Funding

Without public sector resources to support the development and deployment of the CO<sub>2</sub> utilisation sector the growth in the re-use of CO<sub>2</sub> will be much slower. More than any other Member State, Germany has understood this, and initiated a strong support program with hundreds of millions of Euros at various levels to support the development of CO<sub>2</sub> utilisation. This has led to the deployment of CO<sub>2</sub> utilisation at a demonstration scale, which is expected to lead to a full commercial scale as markets develop. Without the right support, both in terms of funding and in policy, the alternative options of using fossil carbon will remain a preferred option in many cases, due to costs or indeed the inertia of supply chains.



## RECOMMENDATIONS

- Additional research required on the public perception of CO<sub>2</sub> utilisation
- Creation of a continuing platform for CO<sub>2</sub> utilisation actors

Presently there has been little research undertaken on how different groups in society perceive CO<sub>2</sub> utilisation products and processes. It is important to gain this insight, as their view has the potential to accelerate or slow market deployment. For example, potential public concerns about CO<sub>2</sub> utilisation could be identified in time and addressed via campaigns to raise general awareness, and by education of specific groups.

With the aim of ensuring societal uptake of CO<sub>2</sub> utilisation technologies, public awareness needs to be tackled. In parallel, the community needs to ensure that the necessary skills and competencies are developed and that the required human resources exist. For increased deployment to occur, key industrial actors will need to drive forward the deployment of CO<sub>2</sub> utilisation technologies.

However, legislation concerning CO<sub>2</sub> is currently not strong enough to impact the market deployment of CO<sub>2</sub> utilisation or indeed carbon capture at scale; the profitable markets for CO<sub>2</sub> utilisation products are at an early stage of development. Therefore, industrial actors are, on the whole, rationally waiting for profitable markets for CO<sub>2</sub> technologies to develop, potentially through legislative intervention to compel market change.

As part of the development of the sector as a whole, two elements can be considered, namely; public perception and capacity building.

### Public perception

In order to increase the eventual market demand of CO<sub>2</sub> utilisation products, societal awareness of the risks and benefits of the products and the technologies will be crucial. To do that, the benefits and risks of CO<sub>2</sub> utilisation technologies for key stakeholders (public, industrial, financial and political) need to be clearly explained. Whether it is the mineralisation of solid wastes or synthetic fuels or indeed other circular economy products, the public judges innovative technologies by a set of underlying values – including price competitiveness, design, and sustainability. If a product or technology is seen as embodying these, it is more likely to gain societal and therefore market approval. For example: the message for certain CO<sub>2</sub> mineralisation products could be communicated with the message that CO<sub>2</sub> is stored safely and for the long-term. For the processing of CO<sub>2</sub> to chemicals and synthetic fuels, the message would clearly be framed differently, as CO<sub>2</sub> is only stored temporarily and therefore is likely to be emitted to the atmosphere, unless subject to an end-of-life capture process. The message that using CO<sub>2</sub> as raw material results in a net reduction of emitted CO<sub>2</sub>, as compared to a base-case or “business as usual” scenario is similar to the other carbon management strategies including CCS. However, as CCS is primarily focussed on carbon mitigation whereas CO<sub>2</sub> utilisation technologies are focussed on the use of CO<sub>2</sub> as a feedstock, the emphasis for CO<sub>2</sub> utilisation should not be on mitigation. The strengths of CO<sub>2</sub> utilisation are on resource efficiency, feedstock diversification and decoupling economic activity from GHG emissions, instead of CO<sub>2</sub> mitigation per se.

### IDENTIFIED CHALLENGES

- What further research needs to be undertaken to understand the public perceptions of this emerging field?
- What can be done to ensure a positive behaviour towards CO<sub>2</sub> utilisation?
- In which ways can CO<sub>2</sub> utilisation products and processes resonate and connect with people’s values?

It seems obvious to state that the acceptability of new technologies is a crucial aspect for them to succeed in the marketplace, so it also seems strange that many technology developers and policy makers give little thought to this aspect. Therefore, it is important that CO<sub>2</sub> utilisation technologies have their possible impacts communicated clearly, transparently and in a timely fashion. This is also true of the related sector of Carbon Capture and Storage (CCS) technologies, where the areas of commonality and differentiation should be explained to a wider group of stakeholders. Although both are clearly concerned with CO<sub>2</sub>, they have different scales, approaches, impacts and drivers.

In order to design a communication strategy that provides a positive and trusted source of information on the benefits and risks of CO<sub>2</sub> utilisation, a better understanding of the current state of perception from various stakeholder groups should first be undertaken to determine where and how the benefits and risks are currently perceived.

For example, some initial studies about emerging public perceptions of the utilisation of CO<sub>2</sub> have been performed in UK<sup>11</sup>. They conclude that while people tend to have a generally positive attitude towards CO<sub>2</sub> utilisation technologies, there is currently a lack of public awareness and knowledge about these emerging technologies, and that some apprehensions remain when it comes to the behaviour that such technologies will generate in the society (e.g. decrease the 'guilt' of CO<sub>2</sub> emitters). These studies conclude that **further systematic research needs to be conducted with a broader scope and larger sample of stakeholders with divergent educational backgrounds** in order to improve our understanding of emerging public attitudes towards CO<sub>2</sub> utilisation (and different CO<sub>2</sub> utilisation options) and the antecedents of these attitudes. This research approach should be undertaken with parallel science communication activities, leading to increased public understanding and knowledge base.

### Capacity building

CO<sub>2</sub> utilisation needs the development of the underpinning science base in order to produce breakthrough research that leads to step changes in innovation. It is also crucial to ensure that the new skills and competences required for the successful commercialisation and upscaling of CO<sub>2</sub> derived products and processes are available in time too. Many skills are likely to be transferable from other sectors such as the chemical sciences, industrial biotechnology or even the building products sectors, but additional training courses should feed into this and address the knowledge gaps that need filled for the CO<sub>2</sub> sector.

### IDENTIFIED CHALLENGES

- How to ensure that the workforce has the required skills and competences for the integration of new CO<sub>2</sub> processes?
- How to ensure that policy makers have access to credible information to understand the risks and benefits of differing CO<sub>2</sub> utilisation products and processes?
- How to ensure that government bodies and agencies have access to the right and up-to-date expertise and information when drafting their action plans, and when engaging actions at international level?
- How to ensure that the differences between CO<sub>2</sub> utilisation processes and CCS are better understood?
- How to mandate a CO<sub>2</sub> utilisation assessment report for each Member state or region?

<sup>11</sup> Undertaken by Dr Chris Jones et al. at the University of Sheffield

The creation of a range of training courses and materials that can be tailored for different stakeholder groups to promote knowledge transfer throughout Europe is necessary. Consequently, a range of EU-wide training programs to include both short courses targeted at industry and policy makers and longer courses that can be run under higher education timeframes should be created, to provide a means of building capacity. Many CO<sub>2</sub> utilisation technologies are still in the R&D phases or have not yet reached TRL levels that allow for a proven technology to be at commercially viable scales. It is therefore of particular interest to help expand industrial knowledge where industry feels this would be helpful.

Significant expertise already exists in many cases in academic institutes and the SCOT project has started to join some of these together by involving several centres to create a Masters level module in CO<sub>2</sub> utilisation. However, the administration associated with establishing and maintaining formal interlinked higher education programmes across Europe should not be underestimated.

Capacity building for policy makers is also an area of importance. A greater understanding of the differences between CCS and CO<sub>2</sub> utilisation is especially important so that the benefits and risks of each are clearly separated and distinguished in order to avoid inaccurate expectations from either one.

Carbon capture and storage and CO<sub>2</sub> utilisation both concern CO<sub>2</sub>. CCS is a key technology to reduce CO<sub>2</sub> emissions (usually) from large point sources by capturing the CO<sub>2</sub> and subsequently storing it in geological formations, hence it is primarily an emissions mitigation technique. CO<sub>2</sub> utilisation can also involve capturing CO<sub>2</sub> but the CO<sub>2</sub> is subsequently used as a carbon feedstock to create products. As many of these products store the carbon only temporarily, CO<sub>2</sub> utilisation should not be considered primarily a CO<sub>2</sub> mitigation technology, although this is dependent on the CO<sub>2</sub> utilisation product and its end-of-life. CCS and CO<sub>2</sub> utilisation should therefore be regarded as complementary, as their aims and indeed their likely scales are different. Going forward, distinctions between the two technologies must be clearly understood by industry, policy makers and the public to help the development of both sectors.

Having each Member State or region undertake an assessment report of the potential for CO<sub>2</sub> utilisation in their area is a credible method to build capacity within policy circles at a regional level. A more detailed understanding of the CO<sub>2</sub> resources within a region and of the existing CO<sub>2</sub> utilisation sector's industrial and academic capacity is required. The commissioning, undertaking and discussion of a CO<sub>2</sub> utilisation assessment report will have a beneficial effect on the level of knowledge of CO<sub>2</sub> utilisation at a policy level. This is therefore an important step in the development of the sector.



## 2 Technical Research and Innovation Challenges

The technical and innovation challenges for the CO<sub>2</sub> utilisation sector can broadly be thought of as a focus on trying to do more with less (energy or materials). Speeding up reactions, with less need to replace equipment and materials, with less waste or by-products, in a more environmental manner, or with less costly materials are all areas of research. Innovation in reactor design, process intensification and separation techniques will be key technical developments in overcoming the low equilibrium yields of many potential products from CO<sub>2</sub>. The areas detailed in this section should not be taken as a cause for exclusion of other areas of scientific discovery or innovation.

### RECOMMENDATIONS

- Continued and increased levels of national and EU funding for CO<sub>2</sub> utilisation fundamental research targeting (but not exclusively):
  - CO<sub>2</sub> catalytic science
  - CO<sub>2</sub> reaction kinetics
  - Novel CO<sub>2</sub> reaction pathways
  - Novel reactor designs
  - CO<sub>2</sub> process separation techniques
- Direct utilisation paths from impure gas sources (cement, power generation, etc.) in a single process without needing a first CO<sub>2</sub> separation and purification step

Exploiting more sustainable carbon resources such as CO<sub>2</sub> will enable the production of more sustainable chemicals, more sustainable fuels, feedstocks and materials. The benefit of using carbon atoms more than once is the reduced need for carbon atoms from fossil resources. The integration of renewable energy in the CO<sub>2</sub> utilisation sector via the use of renewable hydrogen can also bring added benefits. Driving reductions in net CO<sub>2</sub> emissions and fossil fuel usage in the chemical sector would provide the opportunity to supply knowledge and clean technologies, fuels and feedstocks to other sectors too. Europe's publicly funded scientific and engineering strengths continue to provide fundamental research to underpin innovation in the CO<sub>2</sub> utilisation sector. However, it is also clear that other regions of the world (especially Asia) have grown their capability over the last decade e.g. in areas such as catalyst development. It is therefore vitally important that public funds continue to provide the ability for world class long-term research to be undertaken within Europe, especially as this type of knowledge creation is not commonly funded by the private sector. In terms of

CO<sub>2</sub> utilisation in particular, a greater understanding of the science of dissociation of CO<sub>2</sub> and H<sub>2</sub>O to provide reliable kinetic and mechanistic data will be crucial to drive innovation in the future design of catalysts, process equipment, control systems, and integration with other processes. A greater understanding of the impacts of catalyst structure at various scales would provide a benefit to catalyst innovation too.

**Having this ongoing capability in Europe should be seen as a critical underpinning element of a move to a more circular economy that embraces the re-use of CO<sub>2</sub>**

A better fundamental understanding of the kinetics and thermodynamics of relevant bond-forming and cleavage reactions for CO<sub>2</sub> utilisation would provide a fruitful basis for further research and innovation. Providing a deeper fundamental scientific understanding of CO<sub>2</sub> chemistry and reaction processes are needed to eventually translate through to breakthroughs in process and catalyst improvements.

2.1  
CATALYTIC  
IMPROVEMENTS

**IDENTIFIED CHALLENGES**

- Can catalysts be identified that provide significant improvements in cost, selectivity and reaction rate?
- Can catalysts be developed that function with a less purified CO<sub>2</sub> stream and lower CO<sub>2</sub> concentrations hence negating the need for separate capture and purification steps?

Most CO<sub>2</sub> utilisation routes make use of catalysts to provide increased yields and speed up reactions, giving economic benefits to the reaction and overall process. The rate at which the reaction takes place at a given temperature and pressure can be improved with catalysts e.g. a reaction that would require a greater temperature to be fast enough to be of economic interest, can proceed fast enough at a lower temperature / pressure with the use of a catalyst.

The development of catalysts that require a less purified CO<sub>2</sub> stream will have benefits in terms of the type and cost of CO<sub>2</sub> sources e.g. catalysts that can tolerate the water, SO<sub>x</sub> and NO<sub>x</sub> in a typical flue gas, and that are effective at low CO<sub>2</sub> concentrations would be highly beneficial.

**Improving the turnover rate of reactions.**

Improving the turnover rate of catalysts is a longstanding aim of catalyst innovation. Catalyst development that keeps a required turnover rate at lower temperatures and pressures or at lower concentrations of CO<sub>2</sub> is also an area of interest.

**Improving selectivity**

The minimisation of waste is one of the cornerstone principles of green chemistry. Catalysts ideally need to be developed that will selectively yield a single product. Where this is unfeasible and by-products are produced, these should ideally have an intrinsic economic value in a secondary market, and ideally be cost effective to separate from the main product.

**Improving environmental sustainability**

In catalytic reactions the catalysts can be fully, partly or unrecoverable depending on the reaction processes. If a catalyst is encapsulated in the product and cannot be fully recovered it is advantageous for environmental and cost purposes that the catalyst is derived from an Earth abundant, sustainable source. This could be recovered metals from other processes or industries.

### Improving cost

A number of existing catalysts contain noble or rare elements (which can be suitable for scale-up when recovery is cost-effective), so the development and use of effective, low-cost and Earth-abundant catalysts is viewed as an important target for CO<sub>2</sub> utilisation research. This can be of benefit in terms of an energy input to the system, but may also help in a myriad of other ways including the selectivity of a product at a lower temperature and pressure, and a reduction of capital costs of additional process equipment. Improvement of the turnover number will also provide significant cost benefits (the turnover number of a catalyst quantifies its lifetime as the number of catalytic cycles it can perform before activity is lost).

### Improving lifetime and tolerance to impurities

It is important that the catalysts are stable under the reaction conditions so that they can be used for a long lifetime before the need for regeneration or replacement. Innovative catalysts that are less effected by impurities such as particulate material, SO<sub>x</sub>, NO<sub>x</sub>, sulphur in the diluted CO<sub>2</sub> stream are an advantage. Water is often produced as a co-product in CO<sub>2</sub> utilisation processes and can act as a catalyst inhibitor; therefore, high water stability is a desirable catalyst characteristic.

Other compounds and elements poison rather than inhibit catalysts and render them unable to be regenerated e.g. sulphur. This impacts on the cost and sustainability of the catalyst and overall process, and clearly is of benefit if catalysts can be designed that better cope with the problem of poisoning. The underpinning science knowledge is a key resource to allow the better design of innovative catalysts.

### Improving catalysts that can directly use a diluted CO<sub>2</sub> stream (or over dynamic CO<sub>2</sub> stream conditions)

The ability to utilise variable composition streams of CO<sub>2</sub> (including flue gases) **directly** from industrial processes without having to first purify the stream would have a **significant** economic and environmental benefit to the overall process. Indeed, even without the ability to utilise a particular gas stream directly, designing catalysts that are stable over greater ranges of CO<sub>2</sub> gas stream composition means that the clean-up of the gas stream may not need to be as stringent, which will have a benefit to the overall capital cost and operation of the plant, and potentially create cheaper sources of CO<sub>2</sub>.

The formation of carbon on the surface of a catalyst (coking) can be a problem in certain reactions as it inhibits the activity of the catalyst by blocking the active sites. Carbon-forming reactions are coupled to carbon-consuming reactions and the balance will change depending on the reaction kinetics, process conditions and reactor designs. Designing catalysts to cope with changing process conditions whilst keeping carbon formation to a manageable level is one method, and finding a suitable way to deal with the accumulation of carbon is another. Designing to minimise formation or impact or designing to deal with the results after formation is also true of other inhibitors too.



The majority of the chemicals industry operates on the basis of thermochemical catalysis which is typically enhanced by increasing the temperature and pressure of the reaction conditions to an optimal point. A number of industries also use biochemical catalysts such as in the brewing and pharmaceutical industries. Other active research fields of catalysis include electrocatalysis, photocatalysis and hybrid systems as well as nano-catalysis and the use of synthetic biology to create the products from reactants.

### IDENTIFIED CHALLENGES

- Can fundamental research improve the understanding of the underlying science of electrocatalysis leading to improved processes and catalysts?
- How can synergies between thermo-chemical and synthetic biology pathways for CO<sub>2</sub> utilisation be exploited?
- Can a breakthrough in photocatalysis lead to cost-effective direct transformation of solar energy?

### Electrocatalysis

The co-electrolysis of water and CO<sub>2</sub> has the potential to provide a range of products at higher overall efficiency. Products that can be formed include formic acid, carbon monoxide, methanol, methane and other hydrocarbons, all of which are key intermediates for chemical production. Co-electrolysis could be particularly appealing to Member States with increasing amounts of low-carbon electrical energy generation. Advances are needed to provide stable, inexpensive, selective catalysts so that the full potential of electrochemical reduction can be explored. Early stages of research are required to better understand the impact of morphology on CO<sub>2</sub> reduction, reaction pathways, kinetics and electrocatalyst lifetimes. Understanding the underlying science of electrochemistry will also allow the design of materials that have improved resilience to a range of impurities e.g. sulphur. Development of processes and/or materials (ceramic and polymers) that could enable the one-step production of hydrocarbons/alcohols directly from CO<sub>2</sub> and H<sub>2</sub>O (without the need of Fischer-Tropsch reactor) at the intermediate and low temperature range, would also be advantageous.

### Synthetic biology / biocatalysis

There is a significant amount of ongoing research in the Industrial Biotechnology sector where microbially-produced enzymes are used to catalyse industrial chemical reactions. Microbially produced enzymatic reactions using CO<sub>2</sub> as a substrate are clearly within the area of CO<sub>2</sub> utilisation. It is highly possible that synergies can be exploited between thermo-chemical pathways and synthetic biology pathways for CO<sub>2</sub> utilisation, and this may also prove a fruitful area of research.

### Photocatalysis

The use of light to activate CO<sub>2</sub> is viewed as a particularly important goal to reduce the costs and increase a wider deployment of CO<sub>2</sub> utilisation over the longer-term. If photocatalysts are carefully designed they can be tuned to react to different wavelengths of light to gain maximum efficiency. The development of effective photocatalysis has the potential to greatly increase the utilisation of CO<sub>2</sub>, through the simplification of steps and the potentially increased overall efficiencies and decrease in costs of product formation. Artificial photosynthesis and catalysts for 'solar fuels' are two areas of focus for the direct conversion of CO<sub>2</sub>. Breakthroughs in the cost-effective direct transformation of solar energy at scale would radically alter the CO<sub>2</sub> utilisation-technology landscape and impact on wider energy systems; this is due to the reduction in the need for low-cost low-carbon electricity. However, due to the dilute nature of atmospheric CO<sub>2</sub>, there are increased energy inputs required for air handling for processes using Direct Air-Capture (DAC).

The use of plasmas or electrochemistry are currently both active areas of research, as both offer a potentially more efficient pathway to dissociate CO<sub>2</sub> and H<sub>2</sub>O to syngas (a combination of carbon monoxide and hydrogen), to be used as a chemical building block.

#### IDENTIFIED CHALLENGES

- Can promising plasma reactor research be translated to commercial viability?
- Can the durability of high temperature solid oxide cell systems be improved?

#### Plasma dissociation

Plasma-fluidised bed reactors offer a promising route to maximizing plasma-material interaction in a scalable and industrially viable manner. Innovative reactor designs are needed to be able to steer or control the distribution of electrons in a plasma to stimulate vibrational up pumping / ladder climbing for the efficient vibrational dissociation of CO<sub>2</sub>. Gas separation around the plasma requires innovation to prevent back reactions after dissociation.

Microwave plasma, in particular, is beneficial for the dissociation of CO<sub>2</sub> due to its preferential excitation and vibration of molecules but other plasma generation methods could be useful to reduce the temperature and pressure of the wider process conditions

#### Electrochemical reactions/High temperature solid oxide electrolysis

High temperature (500-900 °C) electrolysis in a solid oxide cell (SOC) can be used to electrolyse carbon dioxide or steam, producing carbon monoxide or hydrogen respectively, or to co-electrolyse the two simultaneously. One of the advantages of co-electrolysis is that syngas is produced directly. This is a precursor to synthetic fuel and is readily converted to methane, methanol or dimethyl ether using existing technology, some with minor adjustments, or to longer chain hydrocarbons using the Fischer-Tropsch process.

Hydrogen produced via electrolysis in either an SOC or PEM electrolyser could also be then used in a reverse water gas shift reactor to reduce CO<sub>2</sub> to CO. At intermediate temperature (400–600 °C), methane can be produced directly in the SOC, along with syngas. The exothermic methanation reaction offsets the endothermic electrolysis reactions, leading to a higher efficiency. Intermediate temperature SOCs are, however, further from commercialisation.

High temperature co-electrolysis of carbon dioxide and steam also has great potential for large scale CO<sub>2</sub> utilisation. Long-term durability and performance of the SOCs are key to commercialisation of this technology. Experimental tests of 1000 hours on electrolysis stacks operated at low current density have shown little or no degradation when inlet gas cleaning is employed. Cycling between fuel cell and electrolysis modes has also shown to dramatically reduce degradation and tests of 4000h of reversible operation showed no degradation to microstructure or resistance.

There are several aspects of the technology which require research attention, primarily around cell degradation lifetime; these are being addressed in a few laboratories around the world. Durability will need to improve if the overall cost at all levels is to be reduced: cell, stack and system. The balance of plant, including thermal management strategies, is critical to maximise the efficiency of the whole system. If the capital outlay was reduced there would be less emphasis on extracting maximum performance for the maximum amount of time. While there is space for research around reducing the cost of the cells and stacks, making systems more economically viable could be achieved by high-volume manufacturing. Novel electrode materials need to

be developed for SOCs, which should exhibit high activity, low tendency for carbon formation, mechanical stability at high temperatures, chemical stability with other reactor components and, stable performance under continuous and intermittent operation.

The ability to control the exact composition of the syngas by altering structural characteristics of electrode materials (tuning the activity of catalytic and electrocatalytic routes) also depends on increasing the fundamental knowledge of the interaction between various parameters such as materials and morphology.



Innovation in process intensification can be due to any number of linked technological improvements that bring about significant changes in process metrics and economics. This can be through inter alia improved design and integration of particular unit operations, to a change in process conditions, the use of more active or selective catalysts, or improvements in methods to decrease the energy required for separation of products from the reactants. Other typical methods to intensify processes are through a switch from batch to continuous processing and changing the scale of the process itself (scaling-up and scaling-down).

Process intensification may focus on an innovative step-change in a particular area, but equally it could be a result of a more holistic development of various materials, equipment and techniques. Success can be measured in one of several ways, such as the size or cost of the process equipment, the energy and catalytic inputs to the process, or the reduction in wastes and by-products, all relative to a common functional unit such as the mass of product produced.

## 2.4 PROCESS INNOVATION

### IDENTIFIED CHALLENGES

- Can innovation in reactor design help CO<sub>2</sub> utilisation processes reach commercialisation?
- Can modular systems be beneficial in the context of CO<sub>2</sub> utilisation?
- Can processes and techniques for separation and purification be developed that are more efficient, selective, more robust to impurities and dynamic reaction conditions, and also able to withstand high-temperature and acid / basic conditions?
- Can CO<sub>2</sub> utilisation processes be designed to be nimble and flexible to take advantage of inputs when they happen to be either available or at lower cost? For example, when there is a potential surplus of low-carbon electricity.

### **Innovation in reactor design**

Reactor design is coupled to the operation of the catalyst, to the control of the process conditions and to the energy and mass flows through the reactor. Having a reaction that is limited by the heat-transfer of the reactor (rather than the catalyst) could benefit from the redesign of the reactor and the use of novel materials. The innovation in materials coupled with innovations in additive manufacturing could allow a greater range of reactor geometries to be explored.

The design of many reactors have been optimised over several reactor generations, with a typical driver of design to upscale the size of the reactor and process equipment to achieve economies of scale. However, the variation in the size and location of many sources of CO<sub>2</sub> suggests that an additional design paradigm of having a highly modular approach would also be beneficial, in order to allow these smaller more distributed sources to be utilised as a raw material too.

Multifunctional reactor design is also a promising area for innovation, where separate unit operations are combined e.g. the reaction and separation operations are combined in a single reactor.

Innovations in reactor designs can allow the (re)use of process heat to boost reaction efficiencies, create novel or hybrid separations, integrate the reaction and separation, heat exchange, or phase transition. Techniques using alternative energy sources (light, ultrasound, etc.), and new process-control methods (like intentional unsteady-state operation) are also areas of research and innovation.

### **Innovation in heat management techniques**

Innovations in reactor designs can also allow the (re)use of process heat to improve overall process efficiencies and perhaps turnover speed in particular. Innovation in measurement and control equipment is also desirable, as well as continued innovation in heat exchange techniques and equipment.

### **Innovation in separation techniques**

Separating the desired products from the remaining reactants can commonly be one of the major costs in both energy and equipment terms along the process chain. Therefore, innovation in product separation is a key area for cost reduction of the final product.

Improving the techniques used for separating products from the reactants or catalysts provides benefits to the process as a whole, through an increase of overall efficiency. Processes and techniques for separation and purification need to be developed that are more efficient, selective, more robust to impurities and dynamic reaction conditions, and also able to withstand high-temperature and acid / basic conditions.

### **Modular equipment design**

Regardless of the improvements to the above areas of process intensification, catalysts, product separation etc. there is an additional belief in the benefits of modular design for the process equipment for the CO<sub>2</sub> utilisation sector. The belief is based on both the cost reductions that may be achievable through a modular approach to equipment manufacture, and also the adaptability that a modular approach would give turnkey providers in matching the process equipment to local conditions. Simply put, if equipment such as the reactor can be made in smaller modular assemblies, then many of the benefits of Europe's wider experience in factory

automation and quality control can be brought to bear to drive competitiveness in this sector too. Having assemblies that can be sent offsite for repair – or swapped in and out of the CO<sub>2</sub> process as demanded may have advantages too, but the main advantages are thought to be in terms of cost reductions and also to potentially allow smaller CO<sub>2</sub> sources to be utilised.

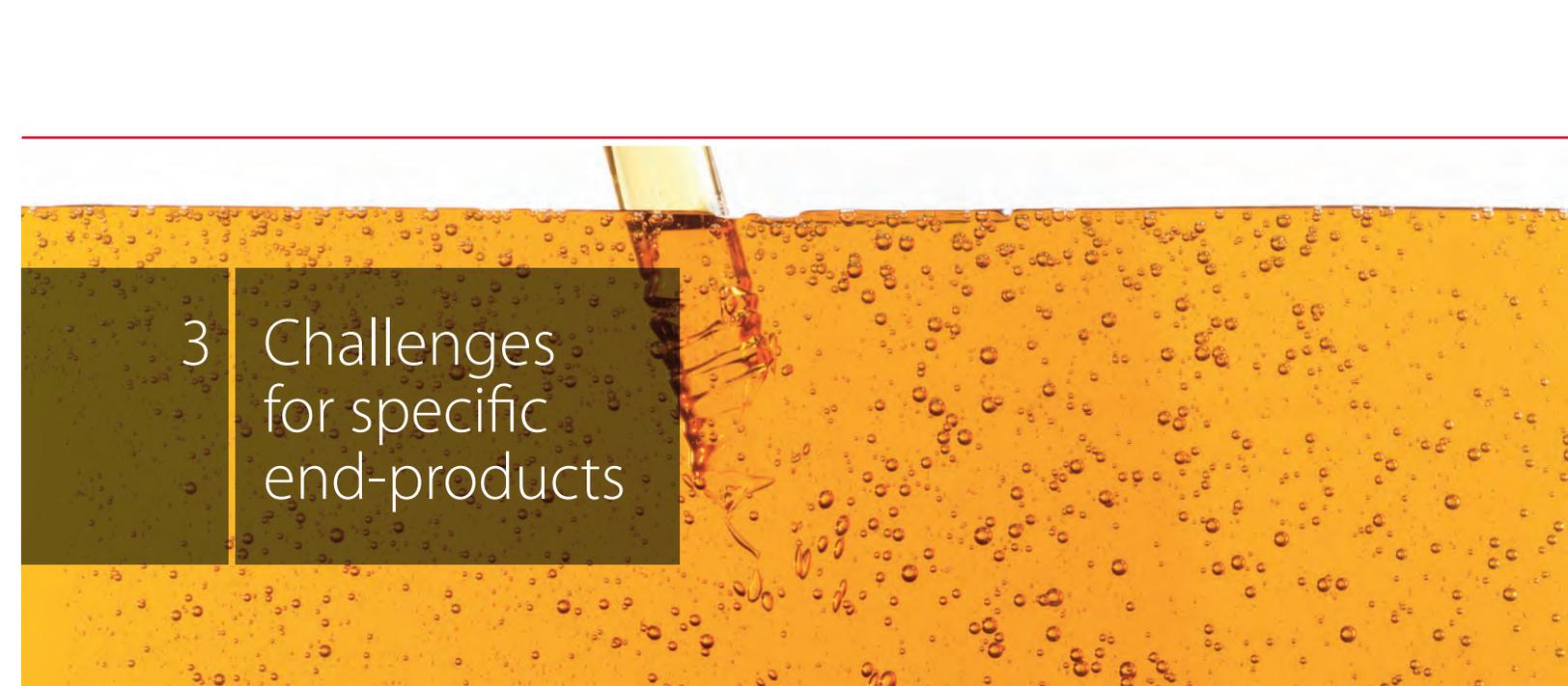
### **Improve process ability to cope with wide ranging and dynamic input conditions**

There are several perceived benefits to developing CO<sub>2</sub> processes that are able to adapt to a range of differing input conditions. One of the major benefits is felt to be in terms of the overall process economics where nimble and flexible processes can take advantage of inputs when they happen to be either available, or at lower cost. For example, when there is a potential surplus of low-carbon electricity, turning down the electrical generation (curtailment) is a way that electrical grid operators can manage their system. A process that can ramp its electrical use up and down may be able to provide technical services (balancing over short periods of time) to the electrical grid through an aggregator. This market requires very tight technical characteristics set by the grid operators, but provides the opportunity to derive a revenue stream in addition to that derived from the sale of the actual product e.g. H<sub>2</sub> or methane.

Future electrical grids are expected to require a greater level of these flexibility services in order to accommodate greater levels of renewable energy generation. So having certain process inputs able to provide flexibility in electrical demand may improve the process economics, however, it is also likely that other parts along the process chain will prefer to have a steadier state operation. Having a range of physical buffers or stores of input or interim products (in order to dampen the immediate effect of changing the electrical demand) allows the areas that can provide flexibility to be separated from those that prefer a more stable operating environment, which is a familiar design problem for process engineers.

Having a process able to be more robust in terms of dynamic conditions is always a trade-off between optimisation in a narrow range of process conditions, versus a less optimal solution over a wider range of conditions. This is also a familiar design problem for process engineers. However, giving more tools to process engineers in the form of more robust catalysts, modular reactors, heat management techniques and control systems should allow a wider range of dynamic conditions to be considered.





## 3 Challenges for specific end-products

CO<sub>2</sub> utilisation enables carbon dioxide to be used as a carbon source for the creation of a wide range of chemical and fuel products. The SCOT project has chosen to highlight several key example CO<sub>2</sub>-derived products that are believed to have the potential to reach commercialisation in Europe with supportive market frameworks in the near to mid-term future. Similar to the previous section, the areas detailed in this section should not be taken as a cause for exclusion of other areas of scientific discovery or innovation. It should be noted that any benefit in net CO<sub>2</sub> emissions is influenced by the product's end use as well as the product itself, with fuels offering a potential net benefit through the re-use of carbon and a delay in emissions, and mineralised wastes offering to lock up CO<sub>2</sub> over decades to thousands of years. These differences highlight the importance of Life Cycle Analysis to clarify the net CO<sub>2</sub> benefit from various CO<sub>2</sub> utilisation products and processes.

The CO<sub>2</sub>-derived products are described, and key research priorities highlighted that if targeted could accelerate its commercial deployment. Some longer-term research areas have also been identified where these processes and techniques are currently at a fundamental research stage.

### 3.1 METHANE

#### Description

Methane (CH<sub>4</sub>) is a simple C1 molecule (with one carbon atom and four hydrogen atoms), it is the main fraction of natural gas and is becoming an increasingly desirable fossil fuel due to its lower carbon-to-hydrogen ratio, its diversity of supply and also its diversity in end uses too. In primary energy terms, it is the third fossil fuel at a global level (behind oil and then coal) and is used in heating, the power sector, as a feedstock for the chemicals sector, and increasingly as a transport fuel.

Methane synthesised by combining CO<sub>2</sub> (or CO) with H<sub>2</sub> can be injected directly into natural gas networks as a drop-in replacement for fossil methane. It therefore offers the ability to use existing natural gas infrastructure (pipelines, storage facilities and end use burners) with little or no changes other than the infrastructure needed for injection.

#### CO<sub>2</sub> utilisation production route

Methane can be produced via the Sabatier reaction which uses elevated temperatures with a metal catalyst e.g. nickel or ruthenium. A source of hydrogen with a low carbon footprint is required such as hydrogen from the electrolysis of water that uses low-carbon electricity.

### Technical Research and Innovation Priorities

- The Sabatier process is exothermic therefore heat management is an important research area when changing the scale of the reactor.
- Development of new reaction pathways such as a co-electrolysis that require water (steam) as an input to the reaction rather than hydrogen.
- Develop CO<sub>2</sub> & H<sub>2</sub>O plasma in direct contact with novel catalyst materials to create a more efficient methane production pathway (as alternative to electrolysis in combination with the Sabatier process).
- Develop photo electrochemical systems (processes or materials) that could enable gas phase operation in the temperature range of 100-200 °C and thus lowering of operating temperature and/or pressure.
- Improve catalyst selectivity and stability.
- Reduce or even avoid the use of noble metals and other expensive elements in the electrodes.

### Policy Priorities

The creation of a market for renewable methane to allow innovative technologies, processes and companies to be deployed at greater scale. The ability for the cost gap between synthetic methane and fossil methane to be reduced is unlikely without the creation of an initial market pull, to allow learning through scaled deployment to occur. The market needs to be large enough to allow meaningful deployment to bring down costs, but due to the sheer size of the methane market, such scale should be achievable without disturbing the overall dynamics of the fossil methane market.

### Description

Methanol is a major intermediate for the chemicals industry and by volume one of the top five commodity chemicals. It is a liquid at standard temperature and pressure and has a much higher volumetric energy density (17.8 MJ/L) compared to methane (0.03 MJ/L). As well as its use as a fuel, solvent, antifreeze and in waste water treatment; methanol is the basis for a large number of chemical derivatives. Methanol can be transformed into hydrocarbons, halides, carbonyls, carboxylic acids, amines and ethers.

### CO<sub>2</sub> utilisation production route

CO<sub>2</sub> can be hydrogenated in the presence of a wide range of catalysts to form methanol. Methanol synthesis requires three molecules of hydrogen per molecule of CO<sub>2</sub>. Two are incorporated into the methanol molecule and the third is used in the production of the by-product, water. Therefore, a source of hydrogen with a low-carbon footprint is necessary.

### Technical Research and Innovation Priorities

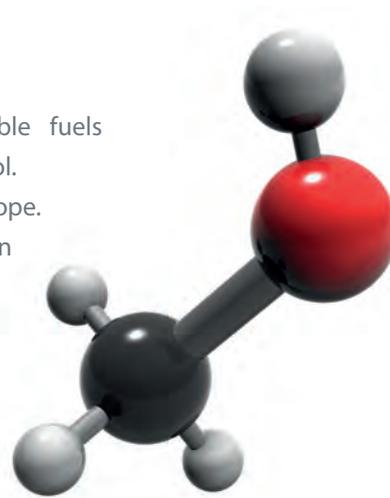
- Develop photo electrochemical systems (processes or materials) that could enable gas phase operation in the temperature range of 100-200 °C and thus lowering of operating temperature and/or pressure.
- Direct processes (starting from methane) with high selectivity and yield.
- Catalyst improvements:
  - Improved use earth abundant catalysts to reduce environmental impact.
  - Improved catalyst activity and selectivity.
  - Improve catalyst yield (at low temperature), turnover rate, selectivity and stability.

## 3.2 METHANOL

- Inverse methanol fuel cells: fundamental research on novel electrodes and membranes.
- Development of micro reactor technologies (and related catalysts) for process intensification on modular small-scale plants.
- High-temperature solid oxide cells: scale-up units and cost reduction.
- Modular process technologies need to be improved / developed.
- Process Intensification of methanol synthesis (design of more efficient reaction and separation equipment)

#### Policy Priorities

- Methanol from CO<sub>2</sub> fully integrated into renewable fuels directives, to increase the potential market for methanol.
- Higher levels of methanol allowed in gasoline mix in Europe.
- Public acceptance and education to complement an increased market pull.



#### Description

Synthetic fuels can be produced from CO<sub>2</sub> and hydrogen often via Fischer-Tropsch reactions to produce long chain hydrocarbons. Synthetic fuels suitable for a range of applications can be produced but key targets are synthetic aviation fuel (kerosene) and synthetic diesel due to their use in the aviation and long haul transport sectors. These two areas are commonly felt to be extremely challenging or unsuitable for other sustainable transport approaches such as electrification.

#### CO<sub>2</sub> utilisation production route

CO<sub>2</sub> can be converted to hydrocarbons using either indirect routes via synthesis gas (syngas) followed by the Fischer-Tropsch process or via methanol synthesis then the MTG (methanol-to-gasoline) process. Direct routes react CO<sub>2</sub> with hydrogen usually in a single reactor with a complex catalyst system.

#### Technical Research and Innovation Priorities

- Minimising production costs via catalyst optimisation and developing new process routes.
- Efficient one reactor CO<sub>2</sub> conversion to higher hydrocarbons.
- Efficient syngas production from CO<sub>2</sub> as input for Fisher-Tropsch synthesis.
- Novel catalyst materials with improved selectivity in chemical synthesis from syngas and other feedstock chemicals to a specific hydrocarbon end-product.
- Find plasma hybrid catalyser combination alternatives for Fisher-Tropsch and Sabatier in order to limit H<sub>2</sub>O production (by-product, energy loss) during hydrogen synthesis to higher hydrocarbons.

#### Policy Priorities

- Synthetic fuels from non-biological origin e.g. derived from CO<sub>2</sub> to be further promoted through renewable fuels directives, to increase the potential market for CO<sub>2</sub> fuels.
- Public acceptance and education to complement an increased market pull.

**Description**

Urea's primary use is as an agricultural fertiliser, but there is an increasing market in the pharmaceuticals, fine chemicals and polymer industries, and as an additive to reduce NO<sub>x</sub> emissions from vehicles. Urea is the largest global bulk product produced from CO<sub>2</sub>. However, a major environmental bottleneck is that the co-reactant is ammonia which is produced by the Haber-Bosch process: the reaction of nitrogen with hydrogen. Presently, the hydrogen is produced from the steam reformation of methane, which produces a significant level of CO<sub>2</sub>, that can then be used in the production of urea. The technical challenge is to eliminate steam reformation from the process and to produce 'green' hydrogen (and hence 'green' ammonia) using water electrolysis powered by renewable energy.

**CO<sub>2</sub> utilisation production route**

Urea is traditionally produced by reacting ammonia produced by the Haber-Bosch process with CO<sub>2</sub>. This is a well-established process that uses the by-product CO<sub>2</sub> produced in ammonia production in urea formation; > 110 Mt of CO<sub>2</sub> are utilised per annum globally. More sustainable routes of hydrogen production that can replace the production route of steam reforming of methane are being developed.

**Technical Research and Innovation Priorities**

Scale up of renewable hydrogen production with reduced CO<sub>2</sub> emissions is urgently required. Development of urea production economically at small scale is required to facilitate distributed production.

**Policy Priorities**

- Legislative subsidies to promote the production of urea with a lower carbon footprint (green urea).
- Approval of green urea for agricultural use for food production.

**Description**

Making plastics more sustainable by using CO<sub>2</sub> as a feedstock is an emerging technology with strong innovation potential. This option is of strategic importance in developing future low carbon and energy footprints materials and technologies. Such materials can be made by direct polymerization of CO<sub>2</sub> or by polymerizing CO<sub>2</sub>-sourced monomers.

**CO<sub>2</sub> utilisation production route**

In the direct approach, CO<sub>2</sub> is used as a monomer in combination with epoxides in the presence of appropriate metal catalysts to produce polymers with CO<sub>2</sub> content up to 50% or low molar mass diol intermediates. Currently, through this concept, batch synthesis of aliphatic polycarbonates and poly(ether-co-carbonates) diol oligomers is under investigation in high pressure demonstration units. Emerging case studies have typically focused on ethylene, propylene or cyclohexene oxide/CO<sub>2</sub> formulations for developing very specific commodity plastics for packaging application or for foams.

**Technical Research and Innovation Priorities**

- The product development, from conception (catalyst identification, optimization) to demonstration in industrial relevant conditions (process intensification, batch or flow reactors conceptions or processes compatible with existing infrastructures)

- Improving properties of Aliphatic polycarbonates via other epoxides or blending with other monomers or polymers is needed.
- The techno-economics for minimizing the process costs and demonstrate economic viability of polymers and monomers (to be considered from the early stages of the research)
- The industrialization and marketing of the products

### Policy Priorities

Labelling mechanism to identify and incentivise polymer products made with CO<sub>2</sub>, to enable to consumer to make informed choices.

### Description

Due to the long-lived nature of the products of mineral and industrial waste carbonation it can be regarded as a potential route to sequester CO<sub>2</sub>. It is therefore of particular interest in CO<sub>2</sub> utilisation as it could be a suitable candidate for CO<sub>2</sub> sequestration for smaller and medium sized emitters that will not be able to connect to CCS infrastructure such as CO<sub>2</sub> transport pipelines that are connected to geological storage.

### CO<sub>2</sub> utilisation production route

There are two main carbonation routes:

#### 1. Carbonation of silicate minerals (engineered or accelerated weathering)

The natural mineral carbonation process of magnesium and calcium bearing silicate minerals is accelerated as well as reducing the amount of energy required in the process. Much research has already taken place in terms of the types of minerals that can be carbonated, how particle size, reaction temperature, CO<sub>2</sub> pressure and chemical agents all affect the reaction speed and efficiency.

#### 2. Carbonation of alkaline industrial wastes

Carbonation of alkaline industrial wastes can render them safer for disposal by reducing or neutralising their alkalinity. Industrial wastes can often contain a high content of cations (e.g. Ca, Mg, Al and Fe) that can react with carbonate ions. However, due to the bulky nature of the industrial waste inputs and products, many of the cost challenges are logistical, such as co-locating a potential industrial waste stream with a suitable source of CO<sub>2</sub> and a potential market for the product, in order to minimise handling and transport costs throughout the supply chain. The transport costs as a fraction of the overall process costs and revenues are helped by increasing the value of the products and reducing the amount of waste for disposal after carbonation.

Although the mineralisation of industrial waste has some challenges, it also has some advantages over other CO<sub>2</sub> utilisation processes. The industrial waste input material is likely to provide a major source of revenue, as waste producers already pay for the waste to be treated or disposed of in some manner. The CO<sub>2</sub> can be from a wide range of sources, with less requirement for pre-treatment. The process is exothermic, therefore the heat produced may be of use for other processes.

### Technical Research and Innovation Priorities

- Widen the range of feedstocks and process conditions to make it less dependent on feedstock specificities.
- Reduce the cost of processing through feedstock selections, process intensification, proper technology choice.

### Policy Priorities

- Harmonisation of end-of-life criteria for wastes between Member States to develop a single market.
- Design policies and propose incentives that promote Industrial Symbiosis, the concentration of industries in close proximity. This must be done in conjunction with the development of processes optimized to use flue gas directly rather than pre-captured CO<sub>2</sub>.
- Promote the benefits of co-processing through appropriate waste policies.
- Promote the use of alternative methods for waste treatment as well as waste policy that rewards the use of alternative materials.
- Waste legislation to avoid landfill of waste containing recoverable resources.
- Relax products standardization procedure to allow the use of a broader range of raw materials with an expected impact on standardisation.
- Stimulate R&D & industry network and R&D centres to improve knowledge sharing
- Enhance capacity building since the development and deployment of mineral carbonation requires a combination of experts from several core disciplines
- Public and industrial acceptance is an important enabler in this conservative industry

### Description

The reaction between epoxides and CO<sub>2</sub> in the presence of a catalyst gives a highly exothermic reaction as the CO<sub>2</sub> is inserted into the epoxide producing cyclic carbonates. Cyclic carbonates have been synthesized in this manner since the 1950's and their production is increasingly expanding due to their use as electrolytes for lithium ion batteries, as solvents, and as an intermediate for polymer synthesis. A breakthrough in this chemistry would also open up opportunities to react CO<sub>2</sub> with amines to form urea and carbamates. Improving water removal should increase the low equilibrium yields in the reactions between alcohols and CO<sub>2</sub> to produce linear or cyclic carbonates (depending on whether the reactant is a mono- or diol). In principle, only one carbonate need be produced by this method; other carbonates can be obtained via transesterification and recycling of the original alcohol (or diol) afterwards.

### CO<sub>2</sub> utilisation production route

- Cyclic carbonates can either be synthesised from CO<sub>2</sub> and epoxides or from CO<sub>2</sub> and monohalohydrins.
- Technical Research and Innovation Priorities
- More energy-efficient synthesis especially of epoxides.
- New synthetic routes for direct synthesis of cyclic carbonate from olefin, CO<sub>2</sub> and O<sub>2</sub>.
- Decreasing energy consumption by decreasing reaction pressures and temperatures while keeping high yields.
- Development of efficient separation procedure for catalyst recycling;
- Overcome the low equilibrium yields via water removal during the reaction possibly via water-permeable.
- Increase knowledge about the kinetics and mechanism of the reaction between CO<sub>2</sub> and alcohols or diols.

## 3.7 CYCLIC CARBONATES

## 4 Conclusion

The SCOT Strategic Research and Innovation Agenda is the first of its kind in the field of CO<sub>2</sub> utilisation. The aim of this document is to give firm guidance by outlining the research and innovation priorities needed to accelerate the sector. As such, this guidance should evolve to consider new areas of research as innovation proceeds and the sector matures.

The SERIA is complemented by the SCOT Joint Action Plan (JAP). The JAP defines the short to mid-term actions required to reach the long-term outcomes detailed in the Vision document, and the research and innovation areas highlighted in this SERIA document. Therefore, SCOT recommends that this document (SERIA) and the JAP are considered together.

The SERIA has highlighted that the successful development of CO<sub>2</sub> utilisation technologies is highly dependent on the way cross-cutting non-technical issues are tackled, as well as the technical advances. It is equally important for greater levels of evidence and understanding to happen in areas such as feasibility studies, policy frameworks and societal challenges, as well as in technical and scientific developments.

## The main research and innovation recommendations from this SERIA are:

- **Establish Shared European Modular Pilot Plant and Verification Centres for CO<sub>2</sub> Utilisation to accelerate innovation and scale up through to the industrial deployment scale.**
- **Establish longer term European and national funding pathways to enable progress from fundamental research to commercialisation.**
- **Promote the publication of Life Cycle Analysis of CO<sub>2</sub>-based processes, especially when publicly funded**
- **Continued analysis of the impact of proposed legislation on the CO<sub>2</sub> utilisation sector.**
- **Provide greater clarity with respect to CO<sub>2</sub> and the circular economy and waste directive legislation.**
- **Harmonisation of end-of-life criteria for wastes between Member States to help develop a single market.**
- **Additional research required on the public perception of CO<sub>2</sub> utilisation**
- **Creation of training courses for the CO<sub>2</sub> utilisation sector**
- **Continued and increased levels of national and EU funding for CO<sub>2</sub> utilisation fundamental research targeting (but not exclusively):**
  - CO<sub>2</sub> catalytic science
  - CO<sub>2</sub> reaction kinetics
  - Novel CO<sub>2</sub> reaction pathways
  - Novel reactor designs
  - CO<sub>2</sub> process separation techniques
  - Direct utilisation paths from impure gas sources (cement, power generation, etc.) in a single process without needing a prior CO<sub>2</sub> separation and purification step

# Appendix 1

## SOURCING RENEWABLE HYDROGEN

Sustainable hydrogen serves as a feedstock for many CO<sub>2</sub> utilisation processes. Fossil-fuel derived hydrogen is not a suitable material for CO<sub>2</sub> utilisation processes in the long-term, unless the carbon is being captured and stored. This is due to the release of CO<sub>2</sub> in the production of hydrogen from current steam methane reforming or coal gasification, which increases the level of CO<sub>2</sub> in the process. To be clear, if CO<sub>2</sub> utilisation processes increase the net level of CO<sub>2</sub> to the atmosphere in comparison to conventional processes, then questions should be raised whether this is appropriate.

A variety of technologies can be considered for hydrogen production. Some use electricity such as water electrolysis, sodium chloride electrolysis and hydrocarbon arc furnace. In other cases, hydrogen is generated as a by-product of an industrial process. The diversification of hydrogen sources is of interest from a business model perspective as this may contribute to reduce the overall cost of the feedstock for the CO<sub>2</sub> utilisation sector. However, in the long term, hydrogen production by means of water electrolysis seems a likely route; as it provides a means to take advantage of low-carbon electricity whilst producing a store of energy such as hydrogen.

There are three main types of electrolyzers: Alkaline Cells, Polymer Electrolyte Membrane Cells, and Solid Oxide Electrolyser Cells. Alkaline Cells are used industrially and so far; it is the only electrolyser technology currently deployed in large scale installations to produce methanol.

To realise the SCOT Vision, pilot/demonstration projects that allow CO<sub>2</sub> utilisation processes to link to different types of electrolyzers will be helpful.

Electrolyzers need to be able to cope with varying renewable supply of electricity. The consequence for electrolysis being powered by weather dependent renewable sources is that the supply of electricity will vary over time and is dependent on the availability of the sun and the wind. During times where renewables are available, the initial start-up of the process and the optimal operating conditions must be reached quickly. All types of electrolyzers are capable of dealing with intermittency, however, there are constraints e.g. Solid Oxide Electrolyser Cells have to be kept at high temperatures while operating in an intermittent mode and equipment lifetimes may be shortened by intermittent operation.

The integration of an intermittently operated electrolyser within the rest of the production system planned for continuous production is another challenge. The easiest way of dealing with this is to store the hydrogen and other feedstocks. Making sure all products (including Oxygen) can be used is another system design challenge.

The size of electrolyzers (surface and volume) will also need to decrease. The footprint of a Solid Oxide Electrolyser (when the technology has further matured) is expected to be lower than that of Polymer Electrolyte Membrane electrolyser which has again a lower footprint than an alkaline

electrolyser. Thus, with regards to the production capacity, the challenge is further process intensification. Materials use and design need to enable a reduction in electrolyser costs.

The electrolyser industry is small and fragmented. Costs have not been driven down through mass production or supply chain optimisation, so there is a great potential for technology improvement. The cost of electrolysers varies across scales and technologies. Lower cost, larger scale electrolysers are required that operate with higher pressures and efficiencies, that can rapidly respond to short-term variations in the electrical price (or even provide an electrical grid balancing service). Cost reduction can be expected as materials evolve, the size of installations increases, and the market for this type of equipment grows.

A reduction in the cost of H<sub>2</sub> production via low-carbon energy sources is of fundamental importance to the chemical production sector as well as the synthetic fuels sector. Besides enabling the production of a range of basic chemicals, cost reduction in hydrogen production will contribute to a large scale deployment of Power-to-X technologies.

Transforming CO<sub>2</sub> into valuable end-products requires energy, often a significant amount of energy, as there can be a high energy penalty (or storage of energy) involved in the upgrading the CO<sub>2</sub> into a valuable product. From the perspective of climate change the energy must come from a lower carbon source in order to limit further emissions of CO<sub>2</sub> to the atmosphere.

## SOURCING LOW-CARBON ENERGY

The frequency of periods of time when the power generated from low carbon sources exceeds the electrical demand is expected to increase, leading to very low, or even negative prices on wholesale markets for electricity. There are three issues related to whether this 'excess' source of electrical energy could benefit the CO<sub>2</sub> utilisation sector.

First, CO<sub>2</sub> utilisation processes such as Power-to-X will have to compete with other dispatchable demands such as power-to-heat, pumped hydro storage, CAES, batteries, electric vehicles and other industrial processes that can take advantage of low-cost low-carbon electricity.

Second, most chemical transformation processes run continuously which reduces the fixed element of the unit cost of production. It would, in most cases, not be feasible to run a CO<sub>2</sub> utilisation plant on the low-cost periods for electricity since the amount of operating hours will be too low for such high investments. Maybe electricity prices would indeed be low for a number of days or hours during the year, but this also implies that for the remaining time of the day the price of electricity is closer to an average price.

Third, zero cost electrical energy does not exist, as there are other costs involved too. The price of electricity on the wholesale market is only one price component of the overall retail price. For example, there are also costs related to the power infrastructure (delivery cost) or levies, which vary between Member States.

Easy, relatively cheap access to (concentrated) carbon dioxide can prove to be a factor of significance in developing CO<sub>2</sub> utilisation activities. The availability of CO<sub>2</sub> by itself will incentivise businesses to start looking for possible opportunities. Carbon dioxide enters the production process at different stages, depending on the selected valorisation route. Each of these valorisation routes will have different requirements in terms of CO<sub>2</sub> purity and concentration and this will further impact individual process steps. The three CO<sub>2</sub> valorisation routes (chemicals, synthetic fuels and mineralisation) are likely to demand a scale much lower than the emissions generated from power plants and other large industrial point sources. Without significant markets for CO<sub>2</sub> utilisation products, the demand of CO<sub>2</sub> for utilisation will only account for small amount of the estimated anthropogenic CO<sub>2</sub> emissions. The supply is therefore much greater than the demand.

The cost of capture depends on the concentration of CO<sub>2</sub>. For high CO<sub>2</sub> concentrations, emitted during natural gas processing, fertiliser plants and other industries, supply is estimated at around 500 million tonnes for an average cost of maximum \$20/tonne. For dilute CO<sub>2</sub> streams emitted by power, steel, cement and other industries, the supply is estimated at around 18,000 million tonnes annually with an average cost of \$50-\$100/tonne<sup>12</sup>. Whether the capture cost will come down depends on how much capture is installed (with few units there is only limited learning). Carbon capture technology will therefore benefit of having an extra demand for CO<sub>2</sub>. At the end of the day, whether the CO<sub>2</sub> is used for storage or utilisation should not be an issue for CO<sub>2</sub> capture development. When there is an increasing demand for CO<sub>2</sub> capture, resulting in more installations and learning, the key point is to decrease the cost for which in turn, both CCS and CO<sub>2</sub> utilisation will benefit.

While in most cases the resource of CO<sub>2</sub> is not a great concern, the cost of sourcing CO<sub>2</sub> will impact the economic viability of CO<sub>2</sub> utilisation. Technologies under development include pre-combustion, post-combustion, and oxy-combustion, which are still expensive. In addition, the type of capture chosen depends on the source of CO<sub>2</sub> chosen which determines the technologies that can be used (for instance, cement plants cannot use pre-combustion) and its costs. Subsequent process integration will require that CO<sub>2</sub> utilisation technologies are able to adapt their location to the different sources of CO<sub>2</sub> available. In the short term, likely sources include CO<sub>2</sub> from the purification of biogas (biomass methanisation), CO<sub>2</sub> from the purification of syngas (from biomass gasification) and captured emissions from concentrated sources (power, industry). In the long run, significant amounts of Direct Air Capture technology could be a possible route to close the carbon cycle and to potentially achieve negative emissions if connected to CCS infrastructure, in order to balance past emissions and fugitive emissions.

12. IASS Potsdam, 2016, [The CO2 Economy – The Transformation of Carbon Dioxide from a Liability to an Asset](#)

Mineral carbonation offers opportunities for process optimisation and/or integration within and across industries and sectors in the context of CO<sub>2</sub> utilisation. It can be applied to a variety of industrial waste materials, which are by-products of high temperature processes (slags, ashes) or tailings from mineral processing operations. Other sources of feedstock include municipal solid waste incinerator ashes resulting from incineration of municipal solid waste, which contains Si, Ca, and a significant quantity of Fe, Al, Na, S, K, Mg, Ti and Cl. Air Pollution Control residues formed in the process of the treatment of flue gases typically contain a mixture of fly ash, unburned carbon and unreacted lime, and is classified as a hazardous waste because of high concentration of heavy metals, soluble salts and chlorinated compounds. Power plant ashes, cement wastes, mining tailing and alkaline paper mill wastes are all potential solid wastes for CO<sub>2</sub> mineralisation.

Compared to natural minerals, these materials have low to negative market prices, present higher reactivity due to their inherent chemical instability and are generated near large CO<sub>2</sub> emitters. Therefore, from both feedstock cost, processing and logistic (extraction costs and waste disposal are avoided or minimized) perspectives, industrial wastes are more interesting than minerals from natural rocks.

Currently, mineralisation technology is demonstrated at pilot scale level (TRL 6-8) and deployed in niche commercial applications (TRL 9) for waste treatment (Waste-to-Disposal and Waste-to-Product), or to improve the process of Portland cement production. In most cases, high purity CO<sub>2</sub> bought from the industrial gas sector is used as the source of CO<sub>2</sub>. This provides greater flexibility in the location of plants, as the transport costs of the solid waste and final product has a major impact on costs.





# Smart CO<sub>2</sub> Transformation

ISBN 9780957258853



ISBN: 978-0-9572588-5-3  
SCOT SERIA Paperback

ISBN 9780957258860



ISBN: 978-0-9572588-6-0  
SCOT SERIA eBook-PDF



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Grant Agreement n° 319995

